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Use of copper slag and washed copper slag as sand in concrete: a state-of-the-art review

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This paper provides the gist of the systematic review undertaken, involving evaluation, analysis, repackaging and modelling of all the literature that could be sourced on the subject. Copper slag (CS) and washed copper slag (WCS), as to be expected, have essentially similar basic physical (although WCS is usually finer than CS) and chemical characteristics and therefore they can be treated as one material. In-depth analysis of 2192 test data sourced from the literature showed that, given all the basic material characteristics, CS/WCS can be used as the sand component for making all strength grades of concrete and giving similar (or in some aspects better) performance to the corresponding concrete made with natural sand. The special attribute of CS/WCS for lowering the mix water demand has been used by the authors to develop two simple models for utilising the potential water savings and estimating the strength gains that can be realised when designing concrete with CS/WCS for given strength at a specific age. It is demonstrated that the water-saving potential of CS/WCS can be used to make other recycled and secondary materials more acceptable for use in concrete.

Introduction

Copper slag (CS) is an industrial by-product obtained during the mette smelting and refining of copper and has an annual production of about 35 million tonnes. This would be sufficient, at 50% replacement of natural sand, for producing about 100 million cubic metres of concrete.

Washed copper slag (WCS) on the other hand is derived by reprocessing (cleaning, washing and drying) CS used in the first place as an abrasive in grit-blast cleaning of ships and refineries (Kua, 2012; Ling and Thim, 1999) and as such, albeit somewhat finer (Holcim (Singapore), 2009). WCS has essentially the same chemical composition as the original CS (Suan *et al.*, 2000) and therefore they can be considered as the same material, possibly with some variations in their particle size gradings.

Over the years efforts have been made to develop the use of CS/WCS, among others, as the sand component for concrete. This development is particularly important as the global sustainability agenda requires all materials to be used appropriately and effectively according to their characteristics, specific attributes and performance in an attempt to move towards the much cherished zero waste scenarios.

This paper provides a state-of-the-art review on the use of CS/CWS as the sand component in concrete. The project was undertaken using a systematic, as opposed to narrative, literature review with an additional specific aim of how best the concrete construction industry can exploit the use of this material and develop it as a value-added resource.

An extensive literature search on the subject identified 97 publications, of which 68 published over the last 25 years, with 2192 test data, were selected for developing the state of the art review using systematic evaluation, analysis, repackaging and modelling of the available data, together with conducting tests on trial mixes in the laboratory to confirm the potential applications of the models developed.

Main characteristics

Copper slag is a non-hazardous material according to the Basel Convention: 1996 (SBC, 1996) and as such can move freely internationally. It is a granular material of essentially concrete sand size fractions and standards (such as JIS A 5011-3:2003 in Japan (JIS, 2003) and KSF 2543:2004 in South Korea) and acceptance criteria (BCA, 2008; Singapore Environment Council, 1992) have been established in some countries for its use in concrete.

The chemical composition of CS and WCS (Table 1) is affected by the composition of copper ore, type of furnace, metallurgical process and treatment process (for WCS). Petrographic examinations suggest that CS/WCS is non-reactive and its chloride and

Oxide: %	Calcium oxide (CaO)	Silicon dioxide (SiO_2)	Aluminium oxide (Al_2O_3)	Iron (III) oxide (Fe_2O_3)	Magnesium oxide (MgO)	Manganese oxide (Mn_2O_3)	Zinc oxide (ZnO)
CS	6·06	33·0	2·79	53·5	1·56	0·01	—
WCS	1·07	32·2	4·50	50·4	0·81	0·05	0·70
Natural sand	3·21	80·8	10·5	1·75	0·77	—	—

Table 1. Typical chemical composition of CS, WCS and natural sand

sulfate constituents comply with BS EN 12620: 12620:2002 +A1:2008 (BSI, 2008) or JIS A 5011-3:2003 (JIS, 2003) (e.g. Ghosh, 2007; Tam, 2001).

The particle size distributions of CS as produced and of WCS as processed (Al-Jabri, 2006; Brindha and Nagan, 2011; Caliskan and Behnood, 2004; Ghosh, 2007; Holcim (Singapore), 2009; Madany *et al.*, 1991; Nazer *et al.*, 2013) were generally found to comply with the medium sand grading for use in concrete according to BS 882:1992 and BS EN 12620:2002 + A1:2008, Figure 1. A measure of the main relevant values for the use of this material in concrete (e.g. Al-Jabri *et al.*, 2009b; Ayano and Sakata, 2000; Brindha and Nagan, 2011; Gorai *et al.*, 2003; Hwang and Laiw, 1989; Khong, 2000; Shoya *et al.*, 2003) is given in Table 2.

Fresh concrete properties

Workability

The use of CS as sand was found to increase significantly the workability of all grades of concrete mixes (e.g. Al-Jabri, 2006; Al-Jabri *et al.*, 2006, 2009a, 2009b, 2011; Ghosh, 2007; Hwang and Laiw, 1989; Khanzadi and Behnood, 2009; Koh and Lye, 2012; Meenakashi and Ilangovan, 2011; Wu *et al.*, 2010a). Although this rate of increase in workability of concrete is

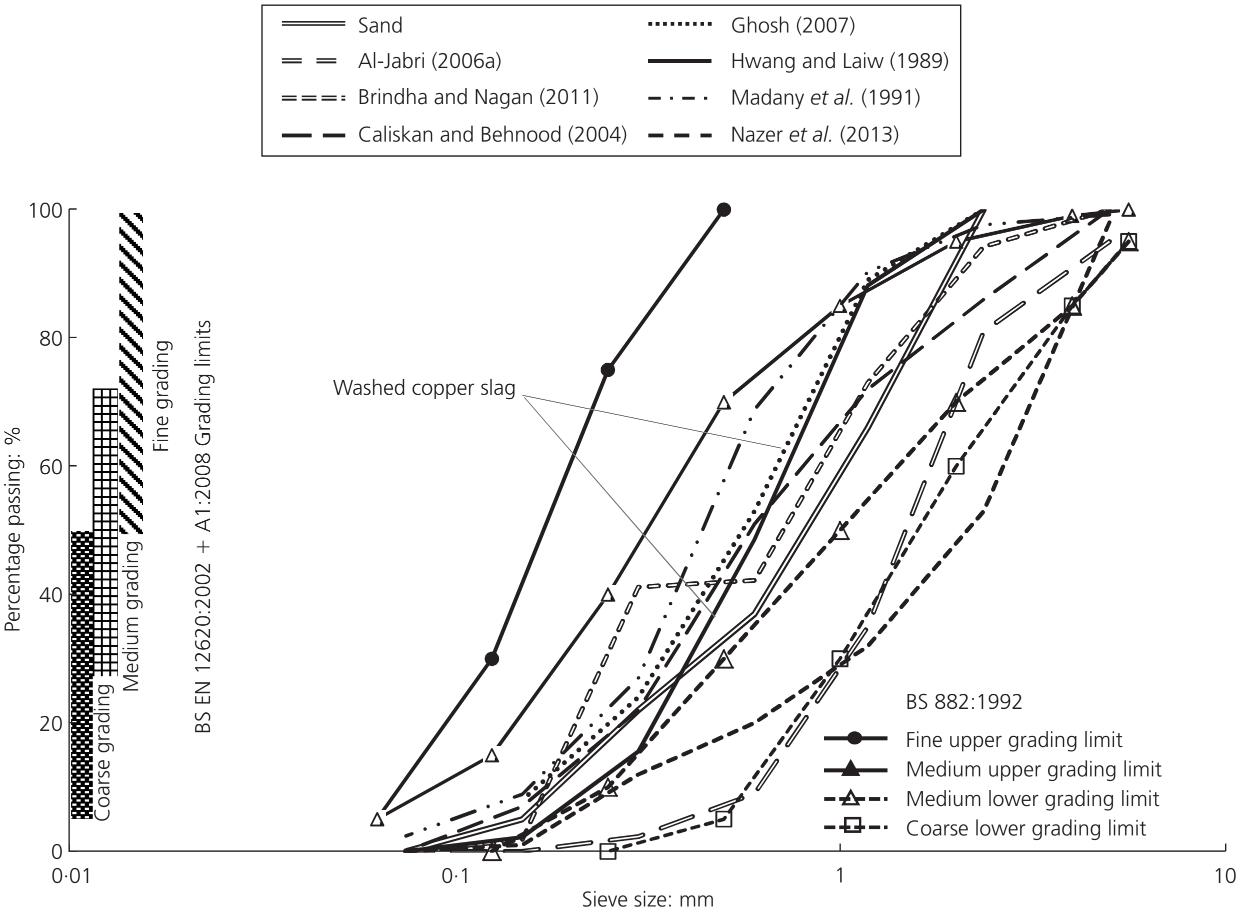

Figure 1. Particle size distribution of CS/WCS

Physical property	Copper slag	Natural sand
Appearance	Black and glassy	Brownish yellow
Hardness, Moh	5–7	—
Particle shape	Irregular	Irregular
Specific gravity	3·97	2·57
Bulk density: kg/m^3	2·08	1·71
Water absorption: %	0·10	0·90

Table 2. Typical physical properties of copper slag sand and natural sand

affected by the design workability grade of the mix, the water/cement (w/c) ratio and the design strength of the mix, as to be expected, do not affect this change.

Improvement in workability has been reported to be associated with the use of CS/WCS as a component of sand. Indeed, this was assumed to be its special characteristic and not the one that is related to its low water absorption, which can only be right when the aggregate is not in a saturated, surface dry condition. Although the real reason for improvement in the workability of concrete made with CS/WCS as sand has not been properly addressed in the literature, it is thought that such an improvement can probably be attributed to the mineralogical composition of the material. CS/WCS has relatively low silica content compared to normal sand (Table 1) and therefore it is likely to be hydrophobic (low affinity to water) in nature (Hicks, 1991). Nevertheless, the authors recognise that this important aspect of the material would benefit from further research to confirm the water affinity factor for CS/WCS.

Stability

All other things being equal, as the specific gravity of CS/WCS is about 45% higher than natural sand, if this difference in densities is not taken into account in designing concrete, as with other materials, it can affect the mix stability, with fresh concrete becoming prone to bleeding and/or segregation and thereby impairing the performance of concrete in the hardened state. There was a clear indication of this happening in some of the studies reported in the literature and this is also mentioned in the durability section later in this paper. Furthermore, as with natural sand, some adjustments to the mix may also be required to minimise its tendency to bleed and/or segregate.

Water-saving potential

Improvement in workability directly offers potential for designing concrete mixes, for a given workability, with reduced mix water content and with it, for a given strength, potential for saving the cement content used, and thereby improving the green image of concrete. This is achievable.

To facilitate this, the test data published in the literature (e.g. Al-Jabri *et al.*, 2006, 2009a, 2009b, 2011; Bahadur and Nayak, 2012; CECRI, 2004; Corugh *et al.*, 2006; Ghosh, 2007; Holcim (Singapore), 2007; Hwang and Laiw, 1989; Khanzadi and Behnood, 2009; Meenakashi and Ilangovan, 2011; Song *et al.*, 2003; Wu *et al.*, 2010a, 2010b) were analysed together with data generated from the dedicated trial mixes tested (Koh and Lye, 2012). A simple model thus developed for use in practice is given in Figure 2.

Applicability of CS potential water-saving model

To test the applicability of this model, two mixes were designed using water savings (Table 3) that can be attained through the use of WCS, as defined in Figure 2. This was used for directly reducing the cement content of the trial mix (WCS-2) and in developing higher strength concrete (WCS-1) without having to increase the cement content of the reference concrete mix, which indirectly delivers the same environmental benefits as WCS-2, Table 3. For example, if cement savings of the kind shown in Table 3 were to be realised across the board, this could potentially yield total cement saving of the order of 5·5 million tonnes per annum and with this saving a similar reduction in quantity of

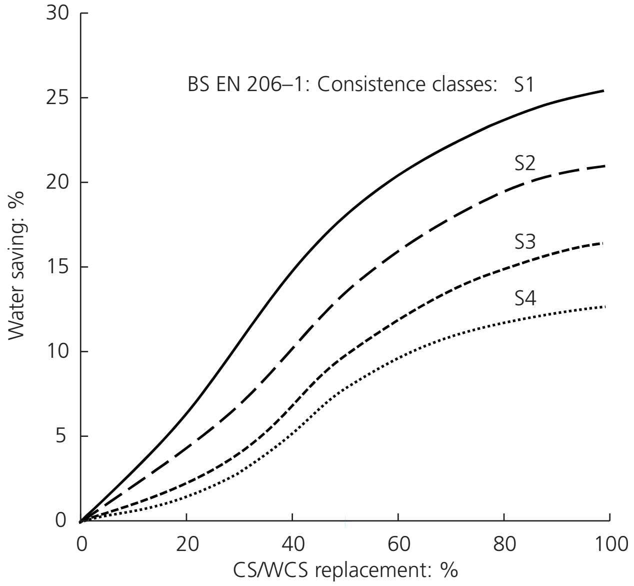

Figure 2. Potential water saving of CS/WCS concrete based on different consistence classes

Concrete	Water: l/m^3	Cement: kg/m^3	28-d strength: MPa
Control	170	380	40·5
WCS-1	145	380	47·5
WCS-2	145	325	42·0

Table 3. Test results of trial mixes made using 50% CS as replacement of natural sand

carbon dioxide emission. Furthermore, the fact that the cement paste content is reduced in both cases should indirectly improve the potential durability of concrete (Dhir and Hewlett, 2008).

The WCS used in the trial mixes in Table 3 was at 50% replacement of natural sand. Although 100% replacement is possible, from the data available, 50% appeared to be an optimum figure.

Further trial mixes were cast using water savings, with the aim to test the potential for using CS/WCS to improve the use of sewage sludge incinerated bottom ash (SIBA) as fine aggregate, and that of recycled concrete aggregate (RCA) as coarse aggregate in concrete, thereby adding considerable value to these three waste materials. In addition to this the use of CS/WCS in designing ultra-high-strength concrete approaching 100 MPa was also attempted.

The mix proportions used in these trial mixes and the strength results obtained are presented in Table 4. The results confirm the suitability of using CS/WCS as value-added material in facilitating

(*a*) the use of SIBA in place of sand in producing structural grade concrete, which otherwise could be difficult, Table 4 (see data under listing (a))
(*b*) the use of RCA as coarse aggregate in all grades of concrete, without having to use additional cement to compensate for the perceived loss in strength, Table 4 (see data under listing (b))
(*c*) the development of ultra-high-strength concrete attaining 100 MPa at 28 d and S3 grade workability without having to use excessively high cement contents and admixture dosages, thereby further improving the sustainability credentials of concrete, Table 4 (see data under listing (c)).

Initial and final settings and hardening

Copper slag and WCS are mentioned widely in the literature in relation to retarding the cement hydration process, which is associated with the presence of heavy metals, such as zinc and lead, and thereby extending initial and final setting times, as well as early strength development. This should be taken into account and, depending upon the replacement level, appropriate steps should be taken when using this material in practice. Notwithstanding, it is suggested that the retardation effect of CS/WCS can be beneficial in hot-weather concreting.

Hardened concrete properties

Strength

The main point to emerge from the analysis of the published studies on compressive strength of concrete and mortar (e.g. Al-Jabri *et al.*, 2006, 2009a, 2009b, 2011; Alnuaimi, 2009; Bahadur and Nayak, 2012; Brindha and Nagan, 2010, 2011; Brindha and Sureshkumar, 2010; Cachim *et al.*, 2009; Ghosh, 2007; Holcim (Singapore), 2007; Hwang and Laiw, 1989; Ishimaru *et al.*, 2005; Koh and Lye, 2012; Lee *et al.*, 2003; Ling and Thim, 1999; Madany *et al.*, 1991; Meenakashi and Ilangovan, 2011; Nazer *et al.*, 2013; Resende *et al.*, 2008; Shoya *et al.*, 1997, 1999, 2003; Song *et al.*, 2003; Sudarvizhi and Ilangovan, 2012; Wu *et al.*, 2010a) is that, even though the researchers did not generally comply with the important requirement of maintaining the particle grading when CS/WCS was used as a component of sand,

Mix	Cement: kg/m^3	Water: l/m^3	w/c	SP[a]	Aggregate: kg/m^3					Slump: mm	28-d strength: MPa
					Coarse		Fine				
					NA	RCA	NA	SIBA	CS		
(a) Testing SIBA and CS											
M1	250	170	0·68	200	1010	—	940	—	—	95	32·5
M2	250	170	0·68	200	1010	—	820	120	—	50	26·5
M3	250	140	0·56	400	1010	—	470	120	475	55	35·0
(b) Testing of use of RCA and CS											
M4	400	180	0·45	650	1010	—	790	—	—	160	65·0
M5	400	180	0·45	700	—	970	790	—	—	145	57·5
M6	400	140	0·35	700	—	970	315	—	665	150	64·5
(c) High-strength concrete											
M7	465	140	0·30	650	1010	—	380	—	555	160	98·8

[a] SP: Superplasticiser (ml/100 kg cement content).

Table 4. A series of trial mixes, using SIBA, RCA and CS/WCS materials

the material can be used effectively for making concrete, provided that good concrete design practice is adopted.

The literature also suggests that the use of CS/WCS should not limit, as for normal sand, the development of strength in concrete. The results of using CS/WCS in self-compacting concrete (Shoya *et al.*, 1999, 2003) suggest that the material is suitable for such applications. Statistical analysis was performed to gauge the overall difference between the strength of concrete made with and without CS/WCS sand for a constant

(*a*) workability, by modifying water content of the mix
(*b*) w/c ratio, without controlling workability.

For completeness, and in order to extend similar analysis to tensile strength, only the papers carrying the data on both the strength properties were selected, even though this reduced the volume of data analysed. The results are presented in Table 5. Some results, for the reasons given in the footnote of the table, have been removed from the analysis. The average values for the CS concrete were as follows

(*a*) constant workability: compressive strength 12% higher than normal concrete and tensile strength, 15%
(*b*) constant w/c ratio: compressive strength 4% higher than normal concrete and tensile strength, 7%
(*c*) overall effect: compressive strength 7% higher than the normal concrete and tensile strength, 10%.

Similar analysis for flexural strength produced essentially similar figures for the performance of CS/WCS when used as sand in concrete, implying that the use of CS/WCS, all things being equal, should produce concrete having at least comparable strength to the corresponding normal concrete.

The only handicap with using CS/WCS as sand in concrete is its retardation effect. Although in some cases this can be an advantage and can remove the need to use a retarding chemical admixture, thereby saving additional cost, the data obtained from the laboratory trials have been used to develop the model given in Figure 3. This shows gain in strength in the subsequent period for the CS/WCS concrete designed to have strength equal to that of normal concrete at a specific age. The design engineer can use this to calculate the ultimate strength of concrete.

It is common for engineers to estimate tensile and flexural strengths of concrete from design codes such as Eurocode 2. Figure 4 plots all the data that can be found in the literature (19 and 16 concrete mix series, respectively, for tensile and flexural strength), covering: CS content 0–100%, w/c ratio 0·27–0·65, strength grade 25–115 MPa, workability including self-compacting concrete. The plotted data also include all high-strength concrete mixes, high-strength concrete with low initial slump and high-performance concrete.

The two relationships obtained (Figure 4), even with somewhat weak correlations of 0·81 and 0·77, for tensile and flexural strength respectively, are considered to be encouraging in that they suggest that CS can be accepted for use as sand in concrete and that Eurocode 2 can be used, in a normal manner, without any modification for estimating the tensile and flexural strengths of such concrete mixes. It should be noted that the results of Meenakashi and Ilangovan (2011) and Sudarvizhi and Ilangovan (2012) for ferrous slag and those of Nazer *et al.* (2013) for mortar were excluded from the relationship for tensile strength and flexural strength, respectively.

For completeness, the results of tensile and flexural strength are shown plotted with the Eurocode 2 correlation in Figure 5. There is a clear suggestion that the flexural strength of concrete made with CS/WCS as sand benefits more than either the tensile strength or the compressive strength.

Considering together all the reported strength results of concrete mixes made with CS/WCS sand at different replacement levels and covering a wide range of w/c ratios, curing, age at testing, it would appear that, provided the material is used correctly and that it is in compliance with specifications for sand for making concrete (particularly in terms of its particle size and grading), design engineers should be able to specify the use of CS/WCS as sand at any replacement level, up to 100%.

Modulus of elasticity

Some studies (Dhir, 2009; Ghosh, 2007; Holcim (Singapore), 2007; Ishimaru *et al.*, 2005; Shoya *et al.*, 1999; Tam, 2001) have suggested the modulus of elasticity (E) improves with the use of CS, in line with strength (σ), but only one study by Ishimaru *et al.* (2005) reported the actual results for the modulus of elasticity of concrete made with CS as a component of sand at 30%.

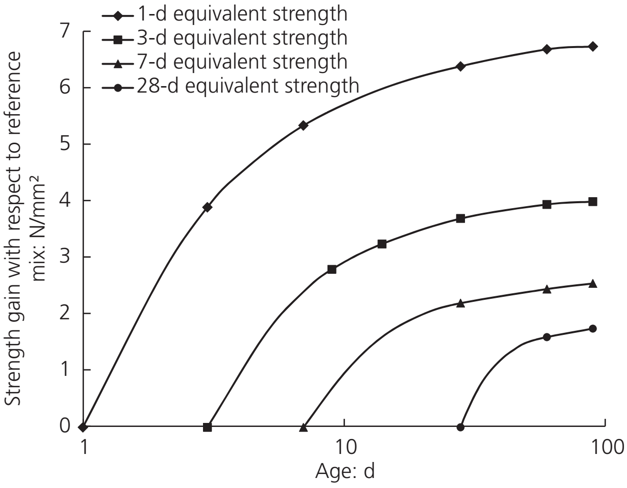

Figure 3. Strength gain of equivalent strength at different ages

Ref.	28-d compressive strength: N/mm^2 Relative strength with respect to normal concrete: %											28-d tensile strength: N/mm^2 Relative strength with respect to normal concrete: %										
	0	10	20/25	30	40	50	60	70/75	80	90	100	0	10	20/25	30	40	50	60	70/75	80	90	100
(a) Constant workability																						
Al-Jabri *et al.*	93·3	—	—	97·4	—	103	—	107	106	—	110·4	4·7	—	—	5·2	—	5·5	—	5·3	5·5	—	5·6
(2009b) HSC	100	—	—	104	—	111	—	115	113	—	118	100	—	–	111	—	117	—	113	117	—	119
Average	100	—	—	104	—	111	—	115	113	—	118	100	—	—	111	—	117	—	113	117	—	119
Individual average											112	Individual average										115
(b) Constant w/c ratio																						
Al-Jabri	44	44·9	48·5	48·9	48·1	53·1	—	46·6	—	50·1	45	3	3·5	3·7	3·2	3·8	4·1	—	3·6	—	3·6	3·4
(2006) NSC	100	102	110	111	109	121	—	106	—	114	102	100	117	123	107	127	137	—	120	—	120	113
HSC	93·9	99·8	95·3	—	79·6	96·8	83	—	79	—	82	5·4	5·2	6·2	—	4·6	6·1	4·8	—	4·7	—	4·4
	100	106	101	—	85	103	88	—	84	—	87	100	96	115	—	85	113	89	—	87	—	81
Al-Jabri *et al.*	45	46	47	—	47·1	47	46	—	34·8	—	35·1	3	3·5	3·7	—	3·8	4·1	3·6	—	3·6	—	3·4
(2011) NSC	100	102	104		105	104	102		77	—	78	100	117	123	—	127	137	120	—	120	—	113
Al-Jabri *et al.*	27·7	33·4	35·7	37·3	45·7	46·3	45·2	51·4	55·5	63·5	69·5	2·6	2·9	3·1	2·9	3·3	3·5	3·7	3·3	3·8	3·9	4·1
(2009b) NSC	100	121	129	135	165	167	163	186	200	229	251	100	112	119	112	127	135	142	127	146	150	158
Al-Jabri *et al.*	93·9	99·8	95·3	—	95·2	96·8	83	—	83·6	—	82	5·4	5·2	6·2	—	6·1	6·1	4·8	—	4·7	—	4·4
(2009a) HSC	100	106	101	—	101	103	88	—	89	—	87	100	96	115	—	113	113	89	—	87	—	81
Alnuaimi	34·4	—	—	—	33·9	—	—	—	31·3	—	—	3·2	—	—	—	2·9	—	—	—	2·7	—	—
(2009) NSC	100	—	—	—	99	—	—	—	91	—	—	100	—	—	—	91	—	—	—	84	—	—
Brindha and	35·1	—	43·4	—	46·7	—	39·7	—	—	—	—	3·35	—	3·96	—	4·58	—	3·92	—	—	—	—
Nagan (2011)		—	124	—	133	—	113	—	—	—	—	100	—	118	—	137	—	117	—	—	—	—
NSC																						
Brindha *et al.*	35	—	43·5	—	46·5	—	39·5	—	—	—	—	3·2	—	3·9	—	4·5	—	3·7	—	—	—	—
(2010) NSC	100	—	124	—	133	—	113	—	—	—	—	100	—	122	—	141	—	116	—	—	—	—
Brindha and	32·7	—	37·93	40·3	43·1	39·1	—	—	—	—	—	3·06	—	5·09	5·37	5·89	4·48	—	—	—	—	—
Nagan (2010)	100	—	116	123	132	119	—	—	—	—	—	100	—	166	175	192	146	—	—	—	—	—
NSC																						
Lee *et al.*	32	—	35	—	—	39	—	40	—	—	40	3·3	—	3·45	—	—	3·65	—	3·82	—	—	3·9
(2003) NSC																						
CS type 1	100	—	109	—	—	122	—	125	—	—	125	100	—	105	—	—	111	—	116	—	—	118
NSC	32	—	38	—	—	38	—	41	—	—	40	3·2	—	3·45	—	—	3·55	—	3·9	—	—	3·85
CS type 2	100	—	119	—	—	119	—	128	—	—	125	100	—	108	—	—	111	—	122	—	—	120
Meenakashi	25·2	38·6	39·9	40·1	43·2	45·3	—	—	—	—	—	4·05	6·3	7·3	7·8	8·05	8·15	—	—	—	—	
and	100	153	158	159	171	180	—	—	—	—	—	100	156	180	193	199	201	—	—	—	—	—
Ilangovan																						
(2011) NSC																						
Shoya *et al.*	37·9	—	—	—	—	—	—	—	—	—	35·22	3·1	—	—	—	—	—	—	—	—	—	3·05
(2003) NSC																						
0·55 w/c	100	—	—	—	—	—	—	—	—	—	93	100	—	—	—	—	—	—	—	—	—	98

Table 5. Statistical analysis of strength data presented in literature by various studies (continued on next page)

Ref.	28-d compressive strength: N/mm^2 Relative strength with respect to normal concrete: %											28-d tensile strength: N/mm^2 Relative strength with respect to normal concrete: %										
	0	10	20/25	30	40	50	60	70/75	80	90	100	0	10	20/25	30	40	50	60	70/75	80	90	100
NSC	31	—	—	—	—	—	—	—	—	—	31·08	2·8	—	—	—	—	—	—	—	—	—	2·71
0·65 w/c	100	—	—	—	—	—	—	—	—	—	100	100	—	—	—	—	—	—	—	—	—	97
Song *et al.* (2003) NSC	53·7	—	55·9	—	—	52·6	—	49·1	—	—	45·8	3·33	—	3·59	—	—	3·3	—	3·03	—	—	2·87
CS type 1	100	—	104	—	—	98	—	91	—	—	85	100	—	108	—	—	99	—	91	—	—	86
NSC	53·7	—	54	—	—	52·1	—	47·9	—	—	43·5	3·33	—	3·4	—	—	3·24	—	2·9	—	—	2·75
CS type 2	100	—	101	—	—	97	—	89	—	—	81	100	—	102	—	—	97	—	87	—	—	83
Sudarvizhi and Ilangovan (2012) NSC	25·2	38·6	39·9	40·1	43·2	45·3	—	—	—	—	—	4·05	6·3	7·3	7·8	8·05	8·15	—	—	—	—	—
	100	153	158	159	171	180	—	—	—	—	—	100	156	180	193	199	201	—	—	—	—	—
Wu *et al.* (2010a) HSC	99	—	98	—	96	—	88	—	70	—	64	5·6	—	5·4	—	5·4	—	5·3	—	4·1	—	4·3
	100	—	99	—	97	—	89	—	71	—	65	100	—	96	—	96	—	95	—	73	—	77
Average	100	104	109	111	108	108	99	108	82	114	94	100	106	112	107	114	115	104	107	90	120	97
Individual average											104	Individual average										107
Overall average											107	Overall average										110

Note: HSC: high-strength concrete, NSC: normal strength concrete. Al-Jabri *et al.* (2009b), Brindha and Nagan (2010), Meenakashi and Ilangovan (2011) and Sudarvizhi and Ilangovan (2012) are excluded from calculation for the following reasons: Al-Jabri *et al.* (2009b) starts with very low slump and has compactability problems; Brindha and Nagan (2010) has a curve that does not follow the general trend; Meenakashi and Ilangovan (2011) and Sudarvizhi and Ilangovan (2012) were conducted in conjunction with ferrous slag. Also note that Shoya *et al.* (2003) is the average results of six different types of CS (different physical properties).

Table 5. (continued)

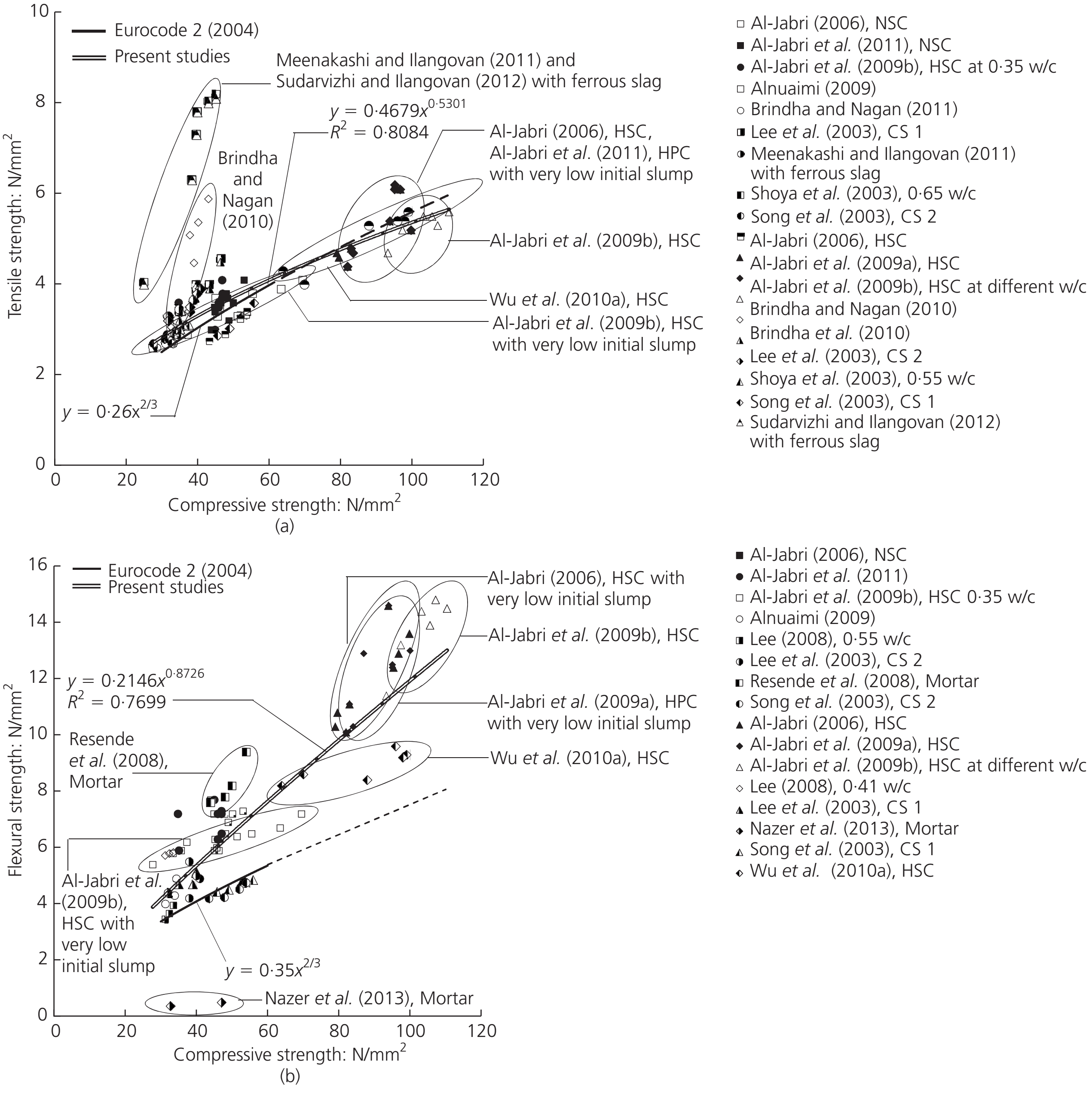

Figure 4. Relationship between compressive and (a) tensile strength and (b) flexural strength of concrete with CS as sand

The results of Ishimaru *et al.* (2005), using two sets of mixes having 0 and 30% CS and w/c ratios of 0·5 and 0·6 with maximum coarse aggregate size of 20 mm and 40 mm, respectively, and tested up to the age of 1 year, together with the Eurocode 2 correlation curve, are shown plotted in Figure 6.

Given the limited data, although it would be wrong to attach too much weight to the trends that appear from Figure 6, particularly how the correlation between E and σ has developed in relation to that in Eurocode 2, the data do suggest that the use of CS/WCS should not adversely affect the elastic deformation of concrete, although further work is needed in this area.

Creep

From the little information available on the subject as summarised in Table 6 (Dhir, 2009; Ghosh, 2007; Holcim (Singapore), 2007; Tam, 2001) it would appear that for a given strength of concrete its creep strain is not likely to vary significantly with the use of CS/WCS as a component of sand.

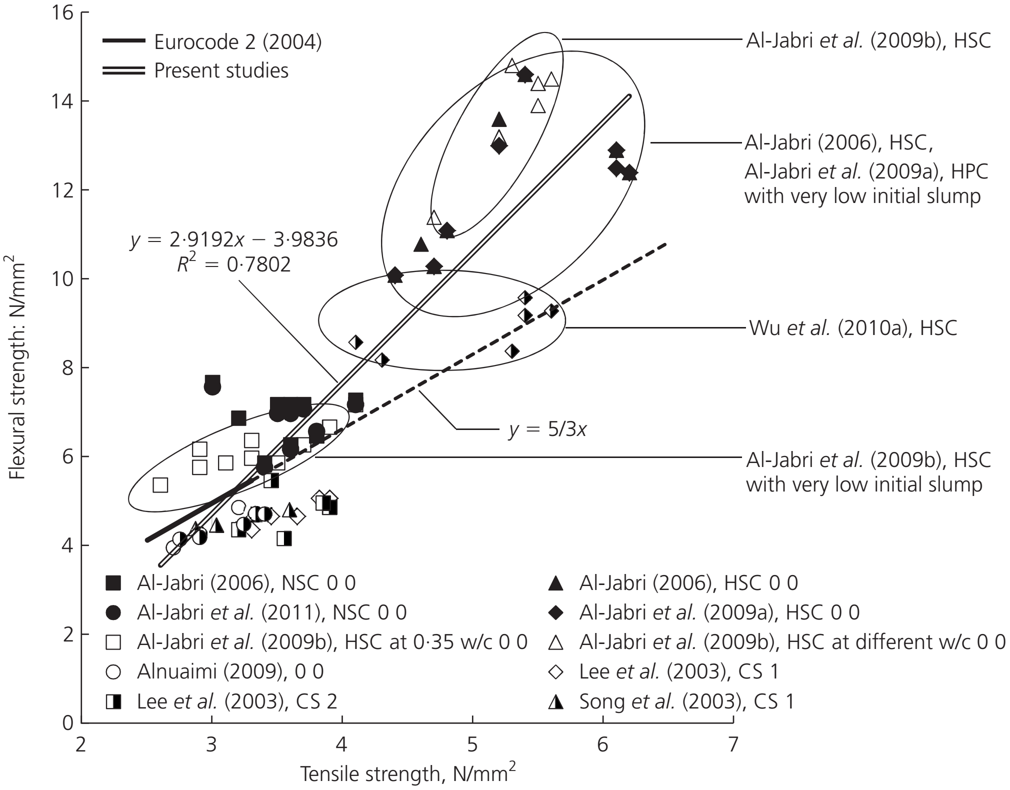

Figure 5. Tensile strength and flexural strength relationship

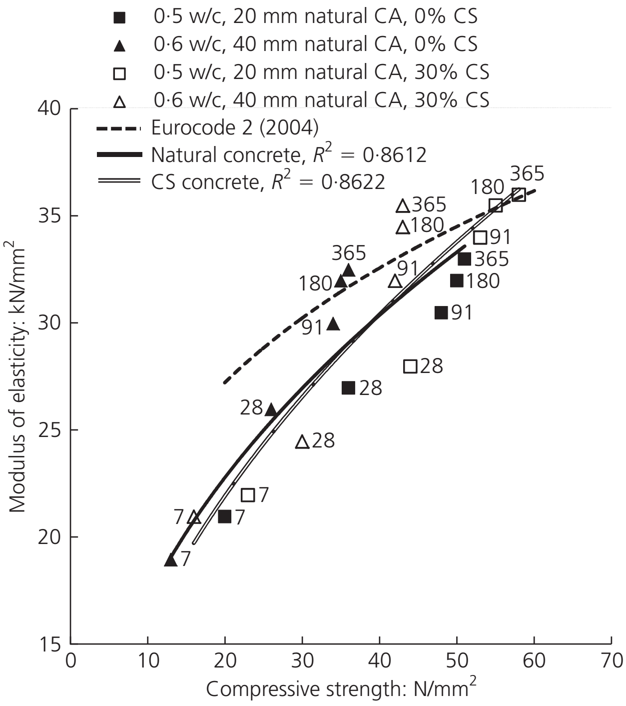

Figure 6. Relationship between compressive strength and *E* modulus

Drying shrinkage

Again, not a substantial amount of information has been published; Table 7 summarises the studies undertaken (Ayano and Sakata, 2000; Ishimaru *et al.*, 2005; Shoya *et al.*, 1999; Tam, 2001). Together with Figure 7 this suggests that there is a general tendency for the drying shrinkage of concrete to reduce with the use of CS/WCS as a component of sand up to 100%. This is what might be expected from the use of fine aggregate which is hard, stable and has a very low absorption property.

These studies also indicated that, as the use of CS/WCS resulted in an increased workability, under the constant workability rule it offered scope for reducing water content of the CS/WCS concrete mixes and thereby further reduced the drying shrinkage of concrete made using CS/WCS as sand content. This makes the use of CS/WCS a more attractive proposition.

Non-destructive testing

As the use of recycled materials gradually becomes accepted in concrete construction, there are likely to be occasions when the integrity of concrete will have to be checked using non-destructive testing. Some studies using rebound hammer (BS EN 12504-2:2012) and ultra-sonic pulse velocity (BS EN 12504-4:2004) tests have published data in this respect (Gupta *et al.*, 2012; Khanzadi and Behnood, 2009; Thomas *et al.*, 2012). The results, although few in number, tend to suggest that the existing

Reference	Studies
Dhir (2009)	Review report As creep reflects the compressive strength, CS concrete deduced to creep less owing to higher strength
Ghosh (2007); Holcim (Singapore) (2007)	NSC, 0·47 w/c for 0% CS and 0·45 w/c for 50% CS According to Neville (1995), creep is influenced by cement paste; therefore, creep of CS concrete was deduced to be similar, as the mix designs were not changed significantly
Tam (2001)	Review report Wee *et al.* (2001) results show that the creep of CS and normal concrete are almost similar

Table 6. Studies reporting on creep of concrete

Reference	Pre-conditioning	Testing condition	w/c	CS: %	Drying shrinkage: μm	Age: d
Ayano and Sakata (2000)	Test age: 14 d	21 ± 1°C, 60 ± 3% RH	0·55	0	600	100
			0·55	100	400	100
Ishimaru *et al.* (2005)	Water cured for 7 d at 20°C	20 ± 1°C, 60 ± 5% RH	0·50	0	900	365
			0·50	30	900	365
			0·60	0	800	365
			0·60	30	750	365
Shoya *et al.* (1999)	Test age: 28 d	20°C, 60% RH	0·55	0	510	100
			0·55	50	530	100
			0·55	100	490	100
Tam (2001)	—	30°C, 65% RH	—	0	< 60	175–350
			—	10	< 60	175–350
			—	30	< 60	175–350

Table 7. Studies reporting drying shrinkage results

correlations used for estimating in situ concrete strength should be applicable to concrete made with CS/WCS. Clearly further data in this respect would help to substantiate this view.

Permeation properties

Together with any chemical reactions that may present a potential threat to the integrity of concrete, such as acid attack and the alkali–aggregate reaction, permeation is usually the essential element of the deteriorating process of concrete. Although limited in scope, several studies have provided information on the effect of using CS/WCS on permeation properties of concrete, namely: initial surface absorption (Al-Jabri *et al.*, 2009a, 2009b, 2011), water absorption (Brindha and Nagan, 2010; Brindha *et al.*, 2010; Dhir, 2009; Gupta *et al.*, 2012; Pazhani and Jeyaraj, 2010; Tam, 2001), permeability (Dhir, 2009; Shoya *et al.*, 1999) and diffusion (Dhir, 2009), see Tables 8–10. The overall impression of the data available and the observations provided by the researchers is that up to about 40% replacement of reference sand with CS/WCS could, to a certain extent, be expected to improve the permeation of concrete, but thereafter, particularly at the very higher end of the CS/WCS replacement level, this process can suddenly cease or reverse.

To ascertain correctly the effect of using CS/WCS on the permeation properties of concrete, the important parameters to consider would be (for a given cement type, w/c ratio, curing and age) the grading of aggregates, and with it their particle packing. Thus, in order to establish the effect of CS/WCS, per se, on the permeation properties of concrete with any test, it would be necessary to keep the sand grading the same in both the reference concrete and the CS/WCS concrete. A closer examination of the published literature revealed that 55% of the papers, although they gave the gradings of both the corresponding reference and CS/WSC sands used, made no attempt in each case to make the two sand gradings similar and thereby eliminate the variations that may arise from the particle packing being different. The other 45% of the papers provided no information on the grading of either the reference or the CS/WCS sands used for the permeation tests.

Durability

Not a great deal of information has been found in the literature on the various aspects of durability of concrete made with CS/WCS sand. However, given that CS/WCS is a sound and hard material, having low porosity compared to most natural sands,

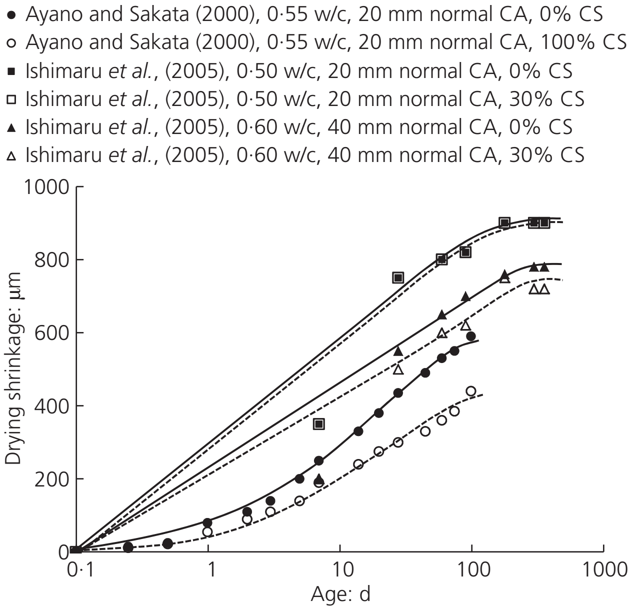

Figure 7. Drying shrinkage of CS and normal concrete

CS content: %	ISA-10: ml/m^2 per s × 10^{-2}		
	NSC 0·50 w/c	HSC* 0·35 w/c	HPC 0·35 w/c
0	36	39	19
10	—	—	17
20	30	—	12
30	—	35	—
40	24	—	11
50	45	30	14
60	50	—	26
70	—	37	—
80	50	34	19
100	78	43	42

*Water/cement ratio (w/c) was adjusted for constant slump.

Table 8. Influence of CS content on ISA-10 of normal strength concrete (NSC), high-strength concrete (HSC) and high-performance concrete (HPC)

CS content: %	Water absorption: %
0	2·3
20	2·1
40	1·8
60	6·0

Table 9. Effect of CS on water absorption of concrete at 60 d

CS content: %	Coefficient of air permeability: m/s × 10^{-13}	Water diffusion coefficient: m^2/s × 10^{-13}
0	2·51	2·43
50	4·17	1·98
100	4·07	1·89

Table 10. Influence of CS content on permeability of self-compacting concrete

provided that good concrete practice is pursued, there would be little merit in undertaking extensive testing of CS sand to establish the durability credentials of CS/WCS.

Carbonation of concrete

Of the eight studies which could be sourced on the subject (Ayano and Sakata, 2000; Dhir, 2009; Ghosh, 2007; Holcim (Singapore), 2007; Lee, 2008; Shi *et al.*, 2008; Shoya *et al.*, 2003; Tam, 2001), only half of them provided the actual test data of the type summarised in Table 11, which is neither extensive nor exhaustive. The remaining studies provided speculative observations based on the characteristics of CS/WCS and its performance in concrete, such as its hardness, absorption and concrete mix water demand, workability and strength. The overall view that can be ascertained from these studies is that the use of CS/WCS in concrete should not, at least, alter the carbonation of concrete.

Chloride ingress

Similarly to carbonation, only few of the studies (Brindha and Nagan, 2011; Brindha *et al.*, 2010; Dhir, 2009; Ghosh, 2007; Holcim (Singapore), 2007; Lee, 2008; Tam, 2001) reported on chloride ingress and provided actual data, Table 11. As for carbonation, and for similar reasons, the use of CS/WCS should not make a significant difference to the resistance of concrete to chloride ingress, although it is believed that when CS/WCS is used effectively as sand it can develop concrete with a somewhat higher resistance than normal concrete to chloride ingress.

Corrosion of reinforcement

Given the chemical and physical nature of CS/WCS, its use as a component of sand at different levels of replacement could hardly be expected to cause any problem with the corrosion of reinforcement in concrete; nevertheless researchers have undertaken some work in this area (Brindha and Nagan, 2011; Brindha *et al.*, 2010; Lee *et al.*, 2003), as outlined in Table 11. Although somewhat faster corrosion with CS/WCS has been recorded, careful examination of the information of the test mixes suggests that this is most likely to be due to the test mixes with CS/WCS not being properly designed and, consequently, they experienced segregation and bleeding. This has most probably impaired the resistance of CS/WCS concrete to corrosion of reinforcement.

Test mixes	Test conditions	Overall observations
1. Carbonation: Ayano and Sakata, 2000; Dhir, 2009[a]; Ghosh, 2007[a]; Holcim (Singapore), 2007[a]; Lee, 2008; Shi *et al.*, 2008[a]; Shoya *et al.*, 1999; Sudarvizhi and Ilangovan, 2012		
w/c ratio: 0·40–0·55 CS content: % – 0, 30, 50, 100 Concrete: CEMI, CEMII; NSC[b], SCC[c]	Accelerated Carbon dioxide: 5, 6, 20% Temperature: 20–30°C; RH: 60–65% Duration: 56, 91, 490 d	No significant difference, with CS concrete on average showing somewhat higher resistance to carbonation
2. Chloride ingress: Brindha and Nagan, 2010[a], Brindha *et al.*, 2010[c]; Dhir, 2009[a]; Ghosh, 2007[a]; Holcim (Singapore), 2007[a]; Lee, 2008; Sudarvizhi and Ilangovan, 2012		
w/c ratio: 0·41–0·55 CS content: % – 0, 30, 50, 60 Concrete: CEMI, CEMII: NSC[b]	Accelerated: RCPT (6 h) (*a*) Immersion test (*b*) 19 380pp[d] (350 d)	No significant difference, with potential for CS to improve resistance to chlorides ingress
3. Corrosion of reinforcement: Brindha and Nagan, 2010; Brindha *et al.*, 2010; Lee, 2008		
w/c ratio: 041–0·55 CS content: % – 0, 20, 30, 40, 50, 60 Concrete: CEMI, CEMII: NSC	Accelerated (*a*) 3·5% Cl, wet/dry, 15 d Galvano static wt loss (*b*) 5% Cl, wet/dry, 30 d	Results show somewhat faster corrosion, but test mixes had some problems
4. Acid resistance: Brindha and Nagan, 2010; Brindha *et al.*, 2010		
w/c ratio: 0·45 CS content: % – 0, 20, 40, 60 Concrete: CEMI; Unstable with CS	Sulfuric acid: 5% diluted having pH value of 2	CS concrete less resistant. Possibly owing to CS mixes experiencing bleeding and segregation in the fresh state
5. Sulfate attack: Ayano and Sakata, 2000; Brindha *et al.*, 2010; Dhir, 2009[a]; Ghosh, 2007[a]; Ishimaru *et al.*, 2005; Holcim (Singapore), 2007[a]; Lee, 2008; Shi *et al.*, 2008[a]; Sudarvizhi and Ilangovan, 2012		
w/c ratio: 0·45 – 0·62 CS content: % – 0, 30, 50, 100 Concrete: CEMI, NSC	Exposed to sodium sulfate (Na_2SO_4), with and without wetting/drying	No significant difference with CS
6. Freeze/thaw: Ayano and Sakata, 2000[a]; Lee, 2008; Shi *et al.*, 2008[a]; Shoya *et al.*, 1997, 1999, 2003[a]		
w/c ratio: 0·41- 0·55 CS content: % – 0, 30, 50, 100 Concrete: CEMI, NSC, Air entrained	Cyclic freezing/thawing ASTM C 666-92 Procedure A Cyclic, −30/18 to 100/40°C	Opinion evenly split, possibly due to the variations in material and test methods
7. Abrasion: Shi *et al.*, 2008[a]; Sudarvizhi and Ilangovan, 2012[a]; Tang *et al.*, 2000		
Mortar strength, 46 MPa	None provided	Use of CS increases abrasion resistance of concrete

[a] No data provided.
[b] Normal strength concrete.
[c] Self-compacting concrete.
[d] Chloride concentration.

Table 11 Summary of the durability studies undertaken using CS as sand

Acid resistance

The main features of the limited research reported in the literature in this area are summarised in Table 11. As in the case of corrosion of reinforcement, owing to the test mixes having not been designed properly, this led the studies in question (Brindha *et al.*, 2010; Brindha and Nagan, 2011) to record a somewhat lower resistance to sulfuric acid for concrete made using CS/WCS as sand.

Sulfate attack

Most of these investigations have been undertaken using sodium sulfate (Na_2SO_4) (Ayano and Sakata, 2000; Brindha *et al.*, 2010;

Dhir, 2009; Ghosh, 2007; Holcim (Singapore), 2007; Hwang and Laiw, 1989; Lee, 2008; Shi *et al.*, 2008; Tam, 2001), with a range of w/c ratios from 0·45 to 0·62, CS content from 0 to 100%, and with and without wetting and drying cyclic action, Table 11. No significant difference was reported for the sulfate attack resistance compared to the corresponding normal concrete.

Freeze–thaw attack

Again, although there is no real reason for undertaking such studies, the research undertaken (Ayano and Sakata, 2000; Lee, 2008; Shi *et al.*, 2008; Shoya *et al.*, 1997, 1999, 2003) (see Table 11), using CS/WCS as sand up to 100% replacement level has proved to be inclusive. However, given the nature of the material, it would be difficult to believe that the use of CS/WCS would reduce concrete resistance to freeze–thaw attack.

Abrasion

Few data have been published on this aspect of durability of concrete made with CS/WCS as sand (Shi *et al.*, 2008; Tam, 2001; Tang *et al.*, 2000), Table 11. The limited results available suggest that the use of CS/WCS greatly improved the abrasion resistance of the mortars tested.

Conclusions

(*a*) Basic characteristics of CS/WCS, in particular its particle size and grading, hardness, volume stability, almost zero water absorption and low mix water demand, make this material potentially well suited for use as sand in concrete. Use of CS/WCS limited to about 50/50 blend with natural sand could perhaps be the best option to maximise the full potential of this material.

(*b*) The use of CS/WCS as a sand component should, if anything, enhance the performance of concrete in the fresh state, particularly workability. In this respect a simple model for estimating potential mix water saving has been proposed and the laboratory trial tests results show how CS/WCS can be used to improve the performance of other waste materials in concrete, as well as in the development of high-performance concrete, in terms of strength and possibly also durability.

(*c*) CS/WCS can be used with any grade of concrete and, except for 1-d strength, such concrete mixes develop strength with time in a normal manner; development of tensile and flexural strengths can be derived using Eurocode 2 procedures. The early age retardation effect can be compensated by reduction in water content, and thereby w/c ratio, which can be done because of the improvement in workability of concrete with the use of CS. A simple model has been proposed to calculate the improvement in ultimate strength development.

(*d*) Concrete made using CS/WCS as a component of sand behaves normally in terms of load-dependent strain, such as elastic strain (modulus of elasticity), creep strain and load-independent strain, such as shrinkage, as well as the impact load-bearing capacity. No special provision should be required in applying non-destructive testing of concrete made with CS as sand.

(*e*) Although it has not been studied widely and/or in great detail, where the material complies with BS EN 12620:2002 – A1:2008, the results suggest that the use of CS/WCS as sand can improve the permeation properties (absorption, permeability and diffusion) of concrete. Similarly, durability properties of CS/WCS concrete could be better or similar to that of the corresponding normal concrete.

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