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Properties of concrete incorporating fine recycled aggregate

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Abstract

The properties of concrete containing fine recycled aggregate are investigated. Recycled aggregate consisted of crushed concrete (CC) or crushed brick (CB) with particles less than 5 mm in diameter. The free water/cement ratio was kept constant for all mixes. The fine aggregate in concrete was replaced with 0%, 25%, 50% and 100% CC or CB. Generally, there is strength reduction of 15–30% for concrete containing CC. However, concrete incorporating up to 50% CB exhibits similar long-term strength to that of the control. Even at 100% replacement of fine aggregate with CB, the reduction in strength is only 10%. Beyond 28 days of curing, the rate of strength development in concrete containing either CC or CB is higher than that of the control indicating further cementing action in the presence of fine recycled aggregate. More shrinkage and expansion occur in concrete containing CC or CB.

Keywords: Expansion; Fine recycled aggregate; Mechanical properties; Nondestructive testing; Shrinkage

1. Introduction

Large quantities of crushed concrete (CC) and brick are produced annually in the UK and elsewhere in the world. Owing to the increasing cost of landfill, the scarcity of natural resources coupled with the increase in aggregate requirement for construction, the use of recycled aggregate to partially replace the virgin aggregate has, therefore, become more common. Indeed, in some European countries, a large proportion of aggregate comes from secondary sources and recommendations for the use of recycled aggregate has been set out by RILEM [1]. Recycled aggregates can be used in low-, intermediate-, and high-grade applications. In the UK, the bulk of current applications for recycled aggregates are carried out at low utilities, such as engineering fill [2]. Concrete, however, is one of the high-grade applications where recycled aggregate can be used.

There have been a number of publications on the use of recycled aggregate in concrete. It was concluded that concrete strength decreases when recycled concrete was used [3] and the strength reduction could be as low as 40% [4,5]. However, no decrease in strength was reported for concrete containing up 20% fine or 30% coarse recycled concrete aggregates, but beyond these levels, there was a systematic decrease in strength as the content of recycled aggregates increased [6]. The strength characteristics of concrete was not affected by the quality of recycled aggregate at high water/cement ratio, it was only affected when the water/cement ratio is low [7,8]. The higher the water/cement ratio, the less reduction in compressive strength [5–7]. On the other hand, the physical properties and the presence of unhydrated cement in recycled concrete aggregate affected the properties of concrete [4]. For concrete containing recycled brick, the strength was unaffected by the strength of brick [8]. In addition, for a given strength, the volume of void, water absorption and sorptivity of concrete containing recycled aggregate reduced with the increase in maximum size of aggregate and was higher for concrete containing crushed brick (CB) [8].

Most of the work on using recycled aggregate in concrete has focused on replacing the coarse aggregate. Therefore, this paper reports the effect of replacing the fine aggregate (sand) with either fine CC or brick on the properties of the concrete. Properties include compressive strength, ultrasonic pulse velocity, dynamic modulus of elasticity, shrinkage and expansion. Correlation between these properties is also conducted. An equation to describe the variation of shrinkage and expansion with time is also considered.

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Table 1
Particle size distribution, water absorption and density of aggregate

Sieve size	Fine aggregate			Sieve size	Coarse Aggregate
	Sand	Recycled			% passing
	(Class M)	Crushed Brick (CB)	Crushed Concrete (CC)		
	% passing				
5 mm	93.1	99.9	99.92	37.5 mm	100
2.36 mm	78.68	53.08	49.48	20 mm	33.47
1.18 mm	71.45	29.14	27.28	10 mm	12.10
600 mic	64.89	17.03	17.26	5 mm	0.00
300 mic	30.06	10.12	9.60		
150 mic	3.66	6.56	6.26		
Absorption (%)	0.8	14.75	6.25	Absorption (%)	0.5
Density (kg/m^3)	2650	2050	2340	Density (kg/m^3)	2650

2. Experimental

2.1. Materials

The mixes' constituents were cement, water, fine aggregate, coarse aggregate and fine recycled aggregate. Portland cement was used. The fine aggregate was class M sand which conformed to BS 882, 1992, and the coarse aggregate was 20 mm nominal size crushed and washed. The recycled aggregates were CC and CB which were obtained from demolished structures. They were further crushed in the laboratory to produce fine CC and CB with particle size of less than 5 mm in diameter. The particle size distribution, water absorption and density of the different types of aggregate are given in Table 1. The particle size distribution of CC and CB is similar but generally coarser than class M sand. The water absorption of CC and CB was 6.2% and 14.8%, respectively, whereas the coarse aggregate and class M sand had a relatively low water absorption of 0.5% and 0.8%, respectively. No data were available on the strength of recycled aggregates.

Table 2
Details of concrete mixes (kg/m^3)

Mix	Mix ID	Cement	Water	Sand (Class M)	Crushed Concrete (CC)	Crushed Brick (CB)	Coarse Aggregate
M1	Control	325	162	649	0	0	1298
M2	CC25	322	161	483	161	0	1288
M3	CC50	320	159	320	320	0	1277
M4	CC75	317	158	158	475	0	1267
M5	CC100	315	157	0	629	0	1257
M6	CB25	319	159	478	0	159	1275
M7	CB50	314	156	314	0	314	1253
M8	CB75	308	154	154	0	462	1232
M9	CB100	303	151	0	0	606	1211

2.2. Mix proportions

Nine different mixes were employed to examine the influence of incorporating fine recycled aggregate on the properties of concrete. Details of the mixes are given in Table 2. The control mix (M1) had a proportion of 1 (cement): 2 (class M sand): 4 (coarse aggregate) and did not include either CC or CB. In mixes M2, M3, M4 and M5, the fine aggregate (i.e., class M sand) was replaced with 25%, 50%, 75% and 100% (by weight) CC, respectively. On the other hand, in mixes M6, M7, M8 and M9, the fine aggregate was replaced with 25%, 50%, 75% and 100% CB, respectively. The free water/cement ratio for all mixes was 0.5.

2.3. Casting, curing and testing

For each mix, 12 cubes of 100 mm in size and four prisms of dimensions $100 \times 100 \times 500$ mm were cast in steel moulds and kept in a mist room at 20 °C and 95% RH for 24 h until demoulding. The cubes and two prisms were then placed in water at 20 °C for a total curing period of 90

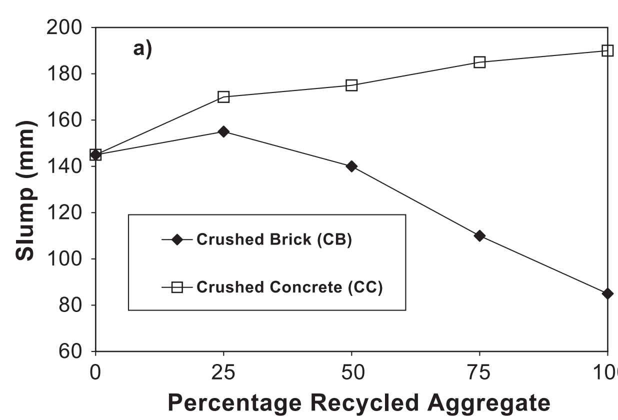

Fig. 1. Effect of recycled aggregates on slump of concrete.

Table 3
Cube compressive strength (S) of concrete

Mix	Mix ID	Compressive strength (N/mm^2) at			
		1 day	7 days	28 days	90 days
M1	Control	11.7	35.6	46.7	51.1
M2	CC25	9.2	25.8	35.3	43.6
M3	CC50	8.9	25.8	35.2	42.1
M4	CC75	8.6	25.5	35.1	39.9
M5	CC100	8.4	25.2	30.0	37.8
M6	CB25	11.2	30.4	39.2	50.9
M7	CB50	10.3	28.5	37.7	48.9
M8	CB75	9.0	26.8	36.1	45.4
M9	CB100	8.0	25.8	33.2	46.7

days. The cubes were used to determine the compressive strength (S) and the two prisms were used to determine the ultrasonic pulse velocity (V), dynamic modulus of elasticity (E_d) and expansion. The remaining two prisms were left to cure in a controlled chamber at 20°C and 60% RH for 90 days and were used to determine the shrinkage. Testing was conducted at 1, 7, 28 and 90 days of curing. In addition, shrinkage and expansion were also monitored between these testing dates. The length change (shrinkage or expansion) was monitored by placing two steel discs on each of the longitudinal faces of the prisms according to BS 1881-117, 1983. The determination of V was according to BS 1881-203, 1986, whereas E_d was determined according to BS 1881-209, 1990 using the following equation:

$$E_d = 4n^2L^2d10^{-15},$$

where E_d is in kN/mm^2, L is the length of specimens in mm, n is the fundamental frequency of the specimens in Hz and d is the density of specimen in kg/m^3.

3. Results and discussion

3.1. Fresh properties

The slump values are plotted in Fig. 1 for concrete containing 0%, 25%, 50%, 75% and 100% CC or CB. At a free water/cement ratio of 0.5, all concretes exhibit good to very good workability without the use of admixtures. The slump varies from 170 to 190 mm for concrete containing CC and from 85 to 155 mm for that containing CB. There is a systematic increase in slump as the content of CC in the mix increases, whereas a decrease in slump is observed with the increase in CB content.

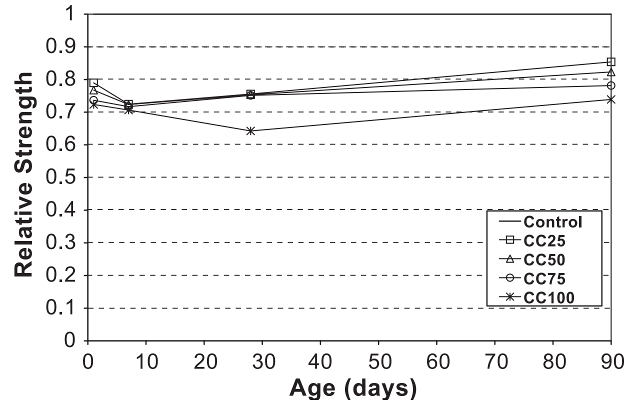

Fig. 3. Relative strength profiles for concrete containing CC.

3.2. Compressive strength (S)

The cube compressive strength (S) for all mixes at 1, 7, 28 and 90 days is presented in Table 3. Generally, S decreases in concrete containing either CC or CB. During the first 7 days, all concretes containing CC exhibit similar S regardless of the CC content. Even at 28 days, S is the same for concrete containing 25–75% CC and is lower at 100% CC replacement compared with all other mixes. At 90 days of curing, an increase in CC content results in S reduction. This is best illustrated in Fig. 2, where S is plotted against CC content at different curing times. The reduction in long-term S ranges from 15% at low CC content (i.e., 25%) to 27% at high CC content (i.e., 100%). The relative strength, which is S for concrete containing CC to that of the control at the same curing period, is shown in Fig. 3. All relative strength values of concrete containing CC do not exceed 1, indicating that S is reduced in the presence of CC. However, the relative strength increases after 28 days of curing. This

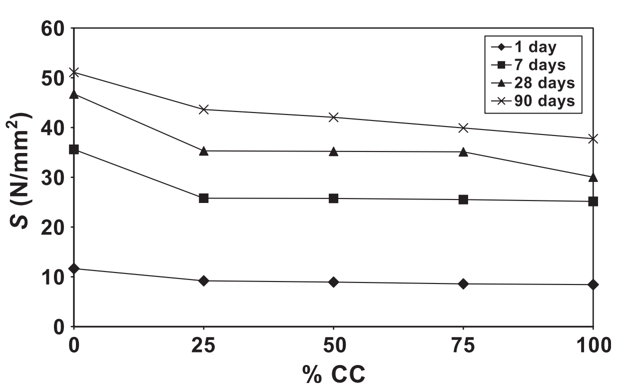

Fig. 2. Effect of CC content on compressive strength (S).

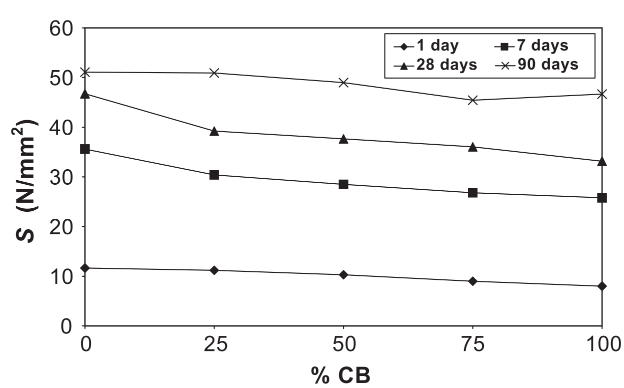

Fig. 4. Effect of CB content on compressive strength (S).

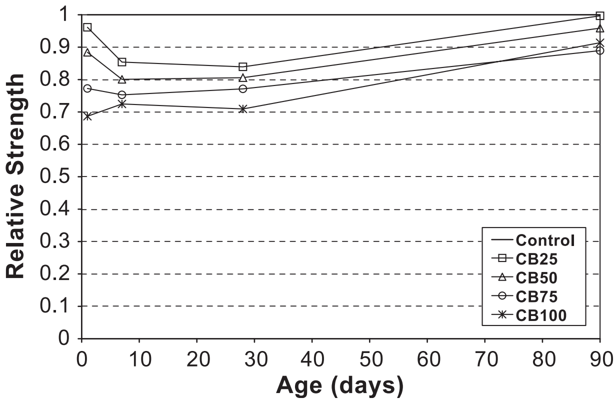

Fig. 5. Relative strength profiles for concrete containing CB.

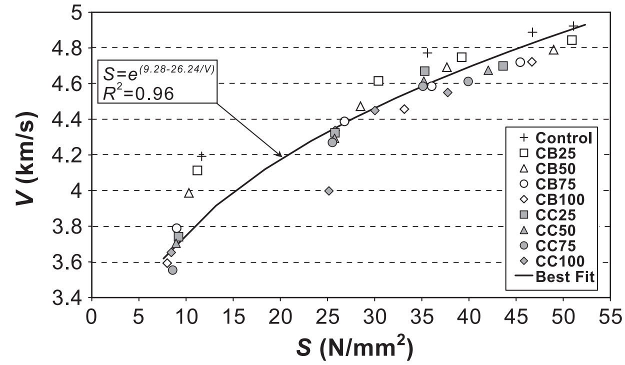

Fig. 6. Correlation between ultrasonic pulse velocity (*V*) and compressive strength (*S*).

might be attributed to further cementing action of unhydrated cement particles in the CC [9].

For concretes containing CB, there is also a systematic decrease in *S* as CB content increases as shown in Fig. 4 where *S* is plotted against CB content. The inclusion of CB in concrete results in a higher *S* as compared with that of concrete incorporating CC at the same replacement level. Between the age of 28 and 90 days, the rate of *S* gain for all mixes containing CB is higher than those containing CC, as shown in Fig. 5, where, the variation in relative strength with curing time for concrete containing CB is presented. This gain in relative strength results in a small difference in long-term *S* between mixes containing CB and the control. Concretes containing 25% and 50% CB show only less than 4% *S* reduction, and at 100% CB replacement, the reduction in *S* is less than 10% as compared with the control. The higher rate of strength development between 28 and 90 days of concrete containing CB is attributed to the pozzolanic reaction caused by the silica and alumina contents of CB and the product of cement hydration (i.e., Portlandite). Wild et al. [10] reported that including ground brick in concrete causes an increase in long-term strength due to its pozzolanic nature.

3.3. Ultrasonic pulse velocity (V)

The variation of *V* with time for all concrete mixes is shown in Table 4. The trend is similar to that observed for *S*. There is a sharp increase in *V* between 1 and 7 days of curing for all concrete. The increase is slowed down between 7 and 90 days of curing. Concretes containing CC or CB reduce *V*. There is a reduction in *V* as the CC or CB content in concrete increases at all curing ages. Concretes containing CB exhibit larger *V* values than those containing CC at the same replacement level.

Fig. 6 shows the correlation between *V* and *S* for all mixes at different curing times. Different best-fit equations to the experimental data were attempted and it was found that an exponential relationship, as suggested by Prassianakis and Giokas [11], of the form: $S = e^{\left(a - \frac{b}{V}\right)}$ fitted best the results obtained with a correlation coefficient R^2=.96, where *V* in km/s, *S* in N/mm^2, constants $a = 9.28$ and $b = 26.24$. These constants were less than those reported elsewhere [11]. Generally, the relationship seems to be independent of CC or CB content, although there is a tendency that the control mix data are above the best-fit line. However, the equation does not seem to fit the early strength data despite the high R^2 value.

3.4. Density (d)

Table 5 presents *d* values in kg/m^3 for all mixes at different curing times. The *d* value ranged from 2263 to 2427 kg/m^3 for all concretes with the control mix exhibiting the largest *d*. A decrease in *d* can be observed as the replacement of sand with either CB or CC increases. A

Table 4
Ultrasonic pulse velocity (*V*) of concrete

Mix	Mix ID	Ultrasonic pulse velocity (km/s) at			
		1 day	7 days	28 days	90 days
M1	Control	4.192	4.772	4.888	4.923
M2	CC25	3.741	4.324	4.670	4.699
M3	CC50	3.704	4.293	4.614	4.675
M4	CC75	3.554	4.270	4.585	4.612
M5	CC100	3.653	3.998	4.449	4.550
M6	CB25	4.113	4.615	4.748	4.844
M7	CB50	3.987	4.473	4.692	4.790
M8	CB75	3.789	4.388	4.585	4.720
M9	CB100	3.593	4.336	4.457	4.722

Table 5
Density *d* of concrete

Mix	Mix ID	Density (kg/m^3) at			
		1 day	7 days	28 days	90 days
M1	Control	2405	2410	2427	2427
M2	CC25	2397	2410	2417	2420
M3	CC50	2373	2373	2383	2383
M4	CC75	2333	2343	2367	2370
M5	CC100	2290	2303	2320	2340
M6	CB25	2393	2397	2400	2404
M7	CB50	2367	2387	2393	2397
M8	CB75	2280	2277	2287	2283
M9	CB100	2263	2260	2267	2280

Table 6
Dynamic modulus of elasticity (E_d) of concrete

Mix	Mix ID	Dynamic modulus of elasticity (kN/mm^2) at			
		1 day	7 days	28 days	90 days
M1	Control	36.5	46.0	48.1	48.3
M2	CC25	30.0	38.5	44.7	44.7
M3	CC50	29.2	37.0	42.5	43.4
M4	CC75	27.9	36.2	42.3	42.5
M5	CC100	27.2	31.4	39.1	40.4
M6	CB25	34.1	43.9	45.7	47.2
M7	CB50	30.5	40.4	45.3	45.9
M8	CB75	28.3	36.7	40.4	43.8
M9	CB100	25.9	36.2	38.1	43.5

slightly lower d is obtained for concrete containing CB as compared with those containing CC at the same replacement level. In addition, there is a slight increase in d with the increase in curing period. A decrease in d for concrete containing CB as compared with those containing CC is not associated with a decrease in S.

3.5. Dynamic modulus of elasticity (E_d)

The E_d values for all mixes are presented in Table 6. Again, and as observed for the S and V, replacing fine aggregate with either CC or CB results in a decrease in E_d. In addition, an increase in replacement level is associated with a decrease in E_d. Concrete containing CB yields higher E_d compared with those containing CC at the same replacement level.

The correlation between E_d and compressive strength for all mixes at different curing times is shown in Fig. 7. The relationship is similar to that of Fig. 6. If a power relationship is fitted to all data as suggested elsewhere [12], the following equation is obtained:

$$E_d = 15.9S^{0.27} \text{ with an } R^2 = .87,$$

where E_d in kN/mm^2 and S in N/mm^2. However, if an equation in the form of $S = ae^{(b-\frac{c}{E_d})}$ is fitted to the experimental data, an R^2 of .93 is obtained with $a = 4.56$, $b = 4.88$ and $c = 108$ indicating a better relationship. This

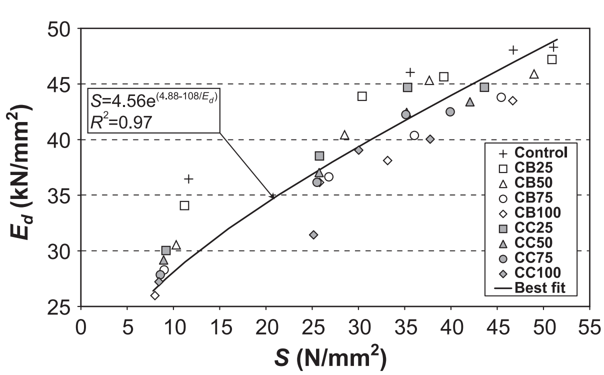

Fig. 7. Relationship between dynamic modulus of elasticity (E_d) and compressive strength (S).

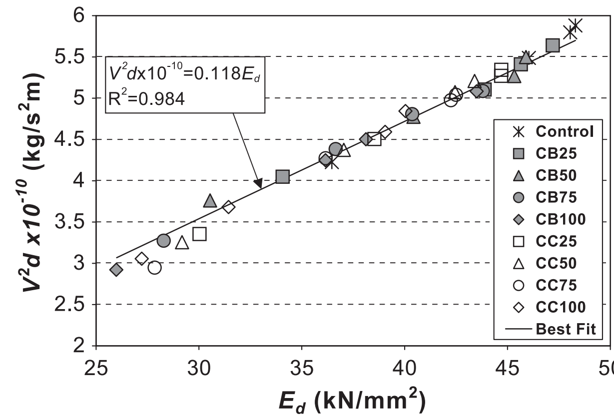

Fig. 8. Correlation between V^2d and E_d.

equation is plotted in Fig. 7. Again, the equation does not seem to fit the low strength data.

Fitting a square root relationship between V and E_d to the data gives: $V = 0.71E_d^{0.5}$ with an R^2 of .97 indicating strong correlation. Lydon and Iacovou [12] reported a similar equation and suggested that a slightly better relationship is obtained if the density of the concrete is included in the relationship. This is presented in Fig. 8 where V^2 multiplied by d is plotted against E_d resulting in the following best-fit equation:

$$V^2d \times 10^{-10} = 0.118E_d, \text{ with an } R^2 \text{ of } .98$$

where V in m/s, d in kg/m^3 and E_d in kN/mm^2, indicating a slightly improved relationship.

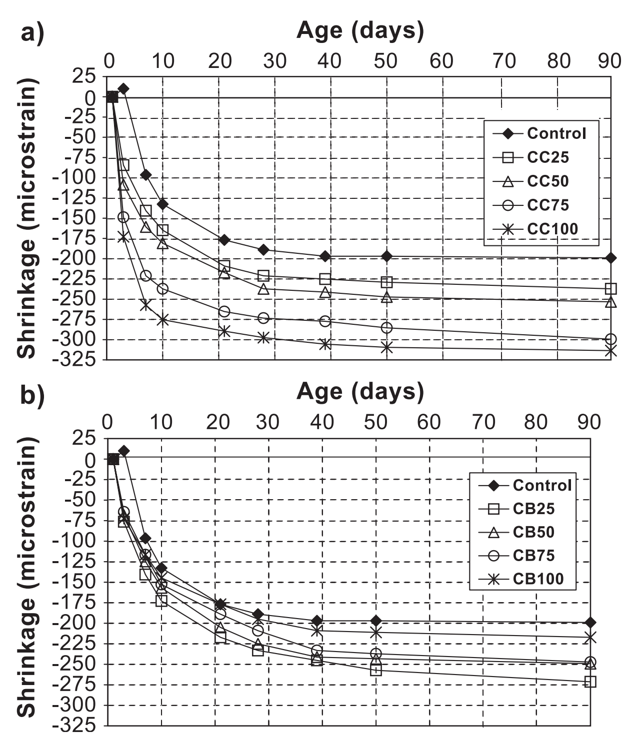

Fig. 9. Shrinkage profiles for concrete containing (a) CC and (b) CB.

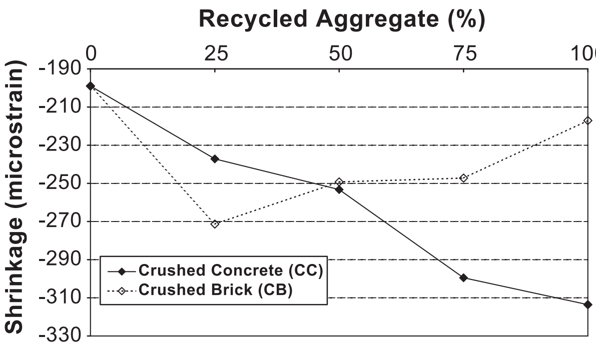

Fig. 10. Shrinkage versus recycled aggregates content at 90 days.

3.6. Length change

Fig. 9 shows the shrinkage profiles for concrete incorporating CC and CB. Most of the shrinkage occurs during the first 10 days for all concretes. Shrinkage is then slowed down. The control mix exhibits the lowest shrinkage. There is a systematic increase in shrinkage with the increase in CC content. This increase is not observed for concrete containing CB as shown in Fig. 9a. As the CB in concrete increases, the shrinkage decreases. This is illustrated in Fig. 10 where the shrinkage is plotted against recycled aggregate content.

To describe the variation of shrinkage with time, an equation in the form of:

$$\varepsilon = \frac{t}{a+t} b$$

was suggested [13,14], where ε is the shrinkage value in microstrain at time t in days, a is a constant related to strength and b is another constant related to ultimate shrinkage values and other factors, including environmental conditions, specimens size and strength. Fitting the above equation to the experimental data, values of a and b were obtained for each of the mixes. These values are presented in Table 7 with their correlation coefficients R^2. The control mix had an R^2 of .97 and all other mixes had an R^2 of .99, indicating strong relationship. The a values varied from 1.65 to 4.36 for concretes containing CC and from 5.45 to 7.32 for those containing CB. The control mix has the largest a value of 9.2. However, all a values reported in this work are less than those reported in the literature. ACI [13] reported a constant value of 45 for a, whereas values above 10 were reported by Huo et al. [14]. On the other hand, the estimated values of b in Table 7 are similar to those reported by Huo et al. [14] and much smaller than those obtained by ACI [13].

Expansion of concrete containing CC and CB is shown in Fig. 11. There is hardly any increase in expansion for

Table 7
Estimation of shrinkage (expansion[1]) of concrete

Mix	Mix ID	$\varepsilon^2 = bt/[a+t]$		
		a	b	Correlation coefficient $[R^2]$
M1	Control	9.2 (0.87)	– 239 (33.3)	.97 (.99)
M2	CC25	4.36 (1.23)	– 250.9 (54.4)	.99 (.99)
M3	CC50	3.43 (1.37)	– 261.4 (50.5)	.99 (.99)
M4	CC75	2.08 (1.08)	– 296.8 (44.2)	.99 (.99)
M5	CC100	1.65 (1.32)	– 319.1 (42.1)	.99 (.99)
M6	CB25	6.03 (1.23)	– 286.6 (44.4)	.99 (.99)
M7	CB50	6.67 (1.58)	– 275.5 (52.7)	.99 (.99)
M8	CB75	7.32 (2.16)	– 269.5 (69.6)	.99 (.99)
M9	CB100	5.45 (3.2)	– 232.6 (88.6)	.99 (.99)

[1] Values in parentheses are for expansion.
[2] ε is the shrinkage (expansion) in microstrain.

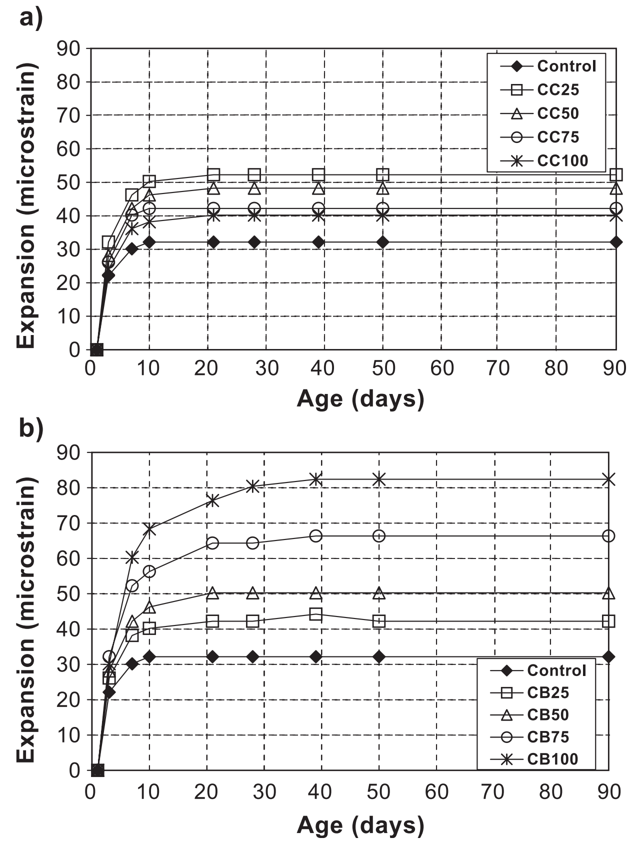

Fig. 11. Expansion profiles for concrete containing (a) CC and (b) CB.

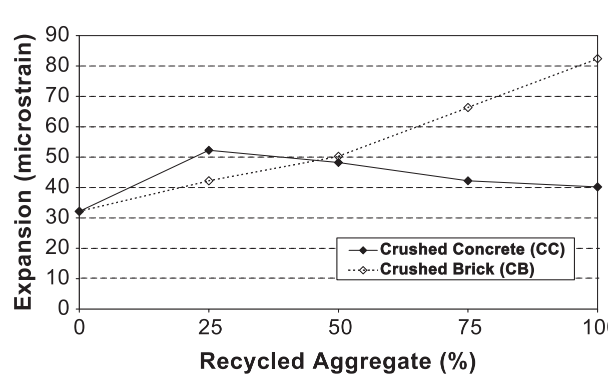

Fig. 12. Expansion versus recycled aggregates content at 90 days.

concrete containing CC after 10 days in water, whereas an increase still exists beyond 10 days for concrete containing CB. The control mix exhibits the lowest expansion compared with the other mixes. An increase in CB content increases expansion, whereas a slight decrease is observed with the increase in CC content as illustrated in Fig. 12 where the expansion at 90 days is plotted for all mixes. The increase in expansion for concrete containing CB might be due to the pozzolanic reaction of CB with the product of cement hydration (i.e., calcium hydroxide) which normally occurs after 28 days. This leads to the production of additional gel, which imbibes more water resulting in more expansion. Figs. 9–12 indicate that, with the exception of the control mix, a higher expansion is associated with lower shrinkage.

A similar equation to that for shrinkage is used to describe the variation of expansion with time. The values in parentheses in Table 7 are for expansion. The R^2 for all mixes is .99. The a values ranged from 0.87 to 3.2 and those for b ranged from about 33 to 89. Small values of a and b indicated less long-term expansion.

4. Conclusions

A systematic reduction in long-term strength occurs when class M sand is replaced with fine CC. This reduction could reach 30% at a replacement level of 100%. A replacement level of 25% causes a reduction of only 15%. Replacing class M sand in concrete with fine CB does not cause substantial reduction in long-term strength even at high replacement levels. With up to 50% replacement, the long-term strength is similar to that of the control, whereas at 100% replacement, a reduction of only less than 10% occurs.

The long-term shrinkage is increased in concrete containing CC or CB. An increase in CC content causes an increase in shrinkage. This is not necessarily the case for concrete containing CB. An initial increase in shrinkage occurs at low CB content, and as the CB content increases, the shrinkage begins to decline. The expansion of concrete increases for concrete containing CC or CB. An increase in CB content causes an increase in expansion. For concrete containing CB, there is a systematic decrease in expansion with the increase in CC content.

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