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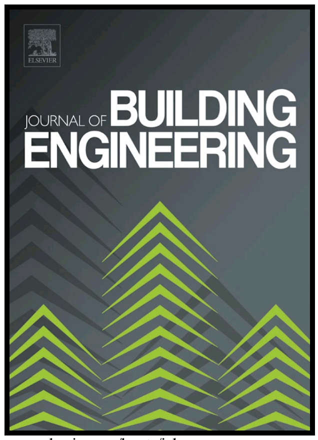

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STRENGTH AND DURABILITY OF CONCRETE CONTAINING CRUSHED CONCRETE AGGREGATES

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CCA exhibits a poorer paste structure and has a greater porosity compared to the control concrete mix. This is due to the localized increase in water-cement ratio around CCA as a result of the water transfer mechanism from aggregates to the paste. This results in a less denser hydrated cement paste with more pores leading to quicker leaching out of calcium from C-S-H and $Ca(OH)_2$. As a result, the acid resistance of CCA concrete decreases with increase in CCA content. The acid resistance improves with the increase in cement content for mixes having same water cement ratio due to improvement of the hydrated paste quality. The increase in water cement ratio for mixes with the same cement content adds to the porosity of the paste structure thereby reducing its acid resistance.

4.10 Chloride permeability

The chloride penetration resistance of CCA concrete decreases with the increase in CCA content and is given in Fig. 11. According to Wang et al. [23], the porosity of the mortar phase due to cracking determines the chloride penetration resistance in concrete. However, Souche et al. [38] proposed that another phenomenon to increase the permeability of concrete is the release of absorbed water from within the aggregates to the cement paste. The porous paste structure resulting from the increase in CCA content is mainly responsible for the increase in chloride permeability. With the increase in water cement ratio, the permeability of concrete increases as result of the porous concrete microstructure. Increasing the cement content for the same water cement ratio reduces the permeability of concrete due to the formation of denser reaction products during the hydration reaction. The permeability of control mixes and the mixes containing CCA lie in the ‘moderate’ range (2000 C to 4000 C) as per ASTM C1202 [21].

5. Strength prediction models

A total of 81 test data from the present study and 392 test data from the published literature ([2]-[3], [13]-[14], [18]-[20], [31], [39]-[70]) were used to develop regression models to predict the strength of concrete containing CCA. The percentage of replacement of natural aggregates is expected to have an inverse relationship on the strength properties of CCA concrete. The strength parameters of concrete containing CCA can be correlated to an equivalent control mix of concrete containing natural aggregates alone. This can be used to predict the expected strength of concrete containing CCA if the strength of the control mix is known a priori. The independent variables considered are the strength parameter ($f_{control}$) of the control mix and the replacement ratio of coarse aggregates.

Statistical F-test was conducted to estimate the significance of the independent parameters which are the strength properties of the control mix and the replacement ratio of coarse aggregate. The results of the F-test are given in Table 5. All the strength parameters, namely, compressive strength, splitting tensile strength, flexural strength and modulus of elasticity of the control mix, were found to have F-value greater than F-critical and P-value less than 0.05. Hence, it can be inferred that the strength parameters of the control mix and the replacement ratio of coarse aggregates influence the magnitude of the corresponding strength parameters in CCA concrete.

Strength prediction models are proposed for the compressive strength, splitting tensile strength, modulus of elasticity and flexural strength of CCA concrete using regression analysis. Table 6 gives the data sets used for the development of prediction of equations for compressive strength of concrete containing CCA. Altogether 160 data sets were used to develop the mathematical model. Table 7 gives the data used for deriving the regression model to predict the splitting tensile strength of concrete. The model was developed by conducting a regression analysis on 103 data sets. A total of 104 data sets including 27 from the present study were used to develop the mathematical model for predicting the flexural strength of CCA concrete. Table 8 gives the details of information data sets used for developing the prediction models for estimating the flexural strength of CCA concrete. Table 9 gives the data used for deriving the regression model to predict the modulus of elasticity of CCA concrete. A total of 106 data sets including 27 from the present study were used for developing the prediction model. The models developed for the prediction of the strength parameters of CCA concrete are given in Table 10. The R^2 value of the prediction models are found to be in the range of 0.987 to 0.999. This indicates that the prediction based on these models can simulate 98.7% variation of the corresponding experimental data.

The predictions based on the models developed in the study were compared with the corresponding experimental results and are given in Fig. 12. The data points were found to be lying within the boundaries indicating ±20% variation. This indicates that the predictions based on the models are in good agreement with the experimental data.

The mean and standard deviation of the ratio between the predicted strength parameter to corresponding experimental value is given in Table 10. It can be inferred from Fig. 12 and Table 10 that the prediction models developed in the study are able to predict the strength parameters of CCA concrete satisfactorily.

6. Mix design of concrete containing CCA

Based on the results of the experimental study, it is found that the strength parameters of concrete are not significantly affected due to the replacement of up to 25% of the coarse aggregates with CCA. However, the strength decreases due to the addition of CCA in concrete. The proposed model can be used to determine the strength of CCA concrete if the strength of control mix and the replacement ratio of aggregates are known. The prediction formula can also be used to calculate the strength of the control mix if we know the target strength of concrete containing CCA. For arriving at the mix proportions of concrete containing CCA, the following steps are suggested.

(1) Decide the target grade of concrete containing CCA and the percentage of replacement of CA (r).

(2) Calculate the grade of control concrete ($f_{control}$) corresponding to the target strength of CCA concrete (f_{cca}) using the proposed prediction formula

$$f_{cca} = f_{control}^{0.95} \times r^{-0.07}$$

The nomogram for the compressive strength of CCA concrete using the above equation is given by Fig. 13. If a designer wishes to prepare M30 grade concrete containing CCA, a horizontal line may be drawn corresponding to r = 0.3 reaching up to the curve marked as 30 in Fig. 13 and the meeting point may be projected down to the axis to get the corresponding strength of the control mix to be used.

(3) Determine the mix proportions of the control mix using the absolute volume method given in IS 10262 [25].

(4) Replace the coarse aggregates as per the replacement ratio (r) decided.

(5) Report the mix proportions of the concrete containing CCA

Thus, the conventional mix design procedure given by IS 10262 [25] can be modified as given in the steps (1) to (5) to arrive at the mix proportions of concrete containing CCA.

7. Conclusions

From the present study, the following conclusions have been arrived at:

- The replacement ratio of aggregates has a significant effect on the strength properties of concrete. Replacement of natural aggregates with up to 25% CCA does not alter the strength properties of concrete remarkably. Beyond 25% aggregate replacement, the compressive strength and modulus of elasticity of CCA concrete are affected.
- The reduction in the splitting tensile strength and the flexural strength of CCA concrete with increase in the percentage of CCA is comparatively lesser than the reduction in compressive strength and modulus of elasticity.
- Durability of CCA concrete decreases with increase in the percentage of CCA in the mix. Higher water absorption by CCA and the presence of porous mortar adhered to the surface affects the durability of concrete.
- Durability of CCA concrete improves with the increase in the cement content of the mix and may be due to the improvement in the quality of the hydrated cement paste and its density.
- CCA concrete with 25% replacement of natural aggregates can be recommended in areas with exposure conditions deemed to be 'Moderate' as per ASTM C1202 [21].
- The models developed in the study are able to predict the strength properties of CCA concrete quite accurately for a wide range of input data.

Crushed concrete aggregates can be used as a sustainable alternative to natural coarse aggregates in concrete and up to 25% of the natural coarse aggregates can be replaced with CCA. For higher values of replacement ratio, modification in the concrete mix design procedure is proposed. The prediction models developed in the study can be utilized to estimate the strength parameters of CCA concrete for any aggregate replacement ratio ($0 < r \leq 1.0$) if the strength properties of the corresponding control mix containing 100% natural crushed stone aggregates are known. The findings of the study encourage the use of concrete containing CCA for structural applications.

LIST OF NOTATIONS

E_c - Modulus of elasticity of the control mix

E_{ce} - Experimental modulus of elasticity of CCA concrete

E_{cp} - Predicted Modulus of elasticity of CCA concrete

f_c - Compressive strength of the control mix

f_{cca} - Strength parameter of CCA concrete

$f_{control}$ - Strength parameter of the control mix

f_{ce} - Experimental compressive strength of CCA concrete

f_{cp} - Predicted compressive strength of CCA concrete

f_r - Flexural strength of the control mix

f_{re} - Experimental flexural strength of CCA concrete

f_{rp} - Predicted flexural strength of CCA concrete

f_t - Splitting tensile strength of the control mix

f_{te} - Experimental splitting tensile strength of CCA concrete

f_{tp} - Predicted splitting tensile strength of CCA concrete

r -Replacement ratio of coarse aggregate by volume

w/c - Water-cement ratio

LIST OF ABBREVIATIONS

CA - Coarse Aggregate

CCA - Crushed Concrete Aggregate

CSA - Crushed Stone Aggregate

OPC - Ordinary Portland Cement

RCPT - Rapid Chloride Penetration Test

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Table 1 Physical properties of cement

Sl. No.	Property	Magnitude
1	Specific gravity	3.15
2	Standard consistency (%)	31.5
3	Initial setting time (min)	130
4	Final setting time (min)	279
5	Compressive strength- 28 days (MPa)	59

Table 2 Physical properties of fine aggregate

Sl. No	Property	Magnitude
1	Specific gravity	2.7
2	Water absorption (%)	1.5
3	Surface moisture	0.5
4	Bulk density– compacted (kg/m^3)	1948

Table 3 Physical properties of coarse aggregate

Sl. No.	Property	Magnitude	
		CSA	CCA
1	Specific gravity	2.72	2.64
2	Water absorption (%)	0.7	6.4
3	Bulk density compacted (kg/m^3)	1832	1487
4	Aggregate crushing value (%)	26	29
5	Surface moisture	Nil	Nil

Table 4 Concrete mix proportions

Sl. No.	Mix	*w/c*	Water kg/m^3	Cement kg/m^3	Fine Aggregate kg/m^3	Crushed Stone Aggregate kg/m^3	Crushed Concrete Aggregate kg/m^3	r^*
1	300/0.4/0	0.4	120	300	763	1366	0	0
2	300/0.4/0.25	0.4	120	300	763	1025	290	0.25
3	300/0.4/0.5	0.4	120	300	763	683	570	0.5
4	300/0.4/1	0.4	120	300	763	0	1150	1
5	350/0.4/0	0.4	140	350	728	1304	0	0
6	350/0.4/0.25	0.4	140	350	728	978	280	0.25
7	350/0.4/0.5	0.4	140	350	728	652	550	0.5
8	350/0.4/1	0.4	140	350	728	0	1090	1
9	450/0.4/0	0.4	180	450	658	1179	0	0
10	450/0.4/0.25	0.4	180	450	658	884	250	0.25
11	450/0.4/0.5	0.4	180	450	658	589	500	0.5
12	450/0.4/1	0.4	180	450	658	0	990	1
13	300/0.45/0	0.45	135	300	748	1340	0	0
14	300/0.45/0.25	0.45	135	300	748	1005	280	0.25
15	300/0.45/0.5	0.45	135	300	748	670	560	0.5
16	300/0.45/1	0.45	135	300	748	0	1120	1
17	350/0.45/0	0.45	157.5	350	711	1273	0	0
18	350/0.45/0.25	0.45	157.5	350	711	955	270	0.25
19	350/0.45/0.5	0.45	157.5	350	711	637	540	0.5
20	350/0.45/1	0.45	157.5	350	711	0	1070	1
21	450/0.45/0	0.45	202.5	450	636	1140	0	0
22	450/0.45/.25	0.45	202.5	450	636	855	240	0.25
23	450/0.45/0.5	0.45	202.5	450	636	570	480	0.5
24	450/0.45/1	0.45	202.5	450	636	0	960	1
25	300/0.5/0	0.5	150	300	734	1314	0	0
26	300/0.5/.25	0.5	150	300	734	985	280	0.25
27	300/0.5/0.5	0.5	150	300	734	657	550	0.5
28	300/0.5/1	0.5	150	300	734	0	1100	1
29	350/0.5/0	0.5	175	350	694	1243	0	0
30	350/0.5/.25	0.5	175	350	694	932	260	0.25
31	350/0.5/0.5	0.5	175	350	694	621	520	0.5
32	350/0.5/1	0.5	175	350	694	0	1040	1
33	450/0.5/0	0.5	225	450	614	1100	0	0
34	450/0.5/0.25	0.5	225	450	614	825	230	0.25
35	450/0.5/0.5	0.5	225	450	614	550	460	0.5
36	450/0.5/1	0.5	225	450	614	0	920	1

*r = replacement ratio of coarse aggregate by volume

Table 5 Test of influence on strength parameters of CCA

Sl. No.	Strength Parameter	No. of samples	r		$f_{control}$		F-critical
			F- value	p- value	F- value	p- value	
1	Compressive Strength	160	1849.3	1.4×10^{-134}	19.2	1.6×10^{-5}	3.87
2	Splitting tensile strength	103	852.4	9.0×10^{-75}	11.6	8.0×10^{-4}	3.89
3	Modulus of rupture	104	1061.9	3.1×10^{-83}	9.6	2.1×10^{-3}	3.89
4	Modulus of elasticity	106	2601.61	2.8×10^{-120}	35.76	9.5×10^{-9}	3.89

Table 6 Details of test data for compressive strength of concrete containing CCA

Sl. No.	Reference	No. of datasets	r (%)	f_c (MPa)	f_{ce} (MPa)
1	Present Study	27	25, 50, 100	34.8-52.8	29.3-50.4
2	Exteberria et al. [3]	1	25	44.4	48.5
3	Verma and Ashish [13]	10	10, 20, 30, 40, 50, 60, 70, 80, 90,100	42.2	34.6-44.6
4	Hamad and Dawi [14]	10	20, 40, 60, 80,100	42.6-72.5	37.2-65.9
5	Rahal [18]	5	100	22.7-53.5	20.3-46.5
6	Saravanakumar and Dhinakaran [20]	3	25, 50, 100	53.7	33.8-42.8
7	Fonteboa et al. [31]	6	20, 50, 100	39.9-56.0	37.7-54.7
8	Dimtriou et al. [39]	2	50, 100	72.1	47.1-53.6
9	Fursule and Shingade [40]	4	20, 30, 40, 50	27.2	24.3-26.9
10	Kou et al. [41]	6	20, 50, 100	48.6-66.8	38.1-62.4
11	Nirmaljeet and Vikram [42]	6	50, 100	32.5-42.9	33.3-39.1
12	Arora and Singh [43]	1	100	41.8	38.1
13	Kabir et al. [44]	1	100	41.0	33.5
14	Wenjian et al. [45]	1	100	43.3	35.9
15	Nandhini et al. [46])	2	100	40.0-46.6	36.6-44.1
16	Abdel-Hey [47]	3	25, 50, 100	27.8	23.7-27.5
17	Gumede and Franklin [48]	5	20, 40, 60, 80, 100	43.0	26.0-37.1
18	Seo and Lee [49]	2	100	48.0-62.4	37.9-50.0
19	Pepe et al. [50]	1	100	41.3	34.4
20	Priscilla and Naik [51]	3	25, 50, 75	33.3	27.1-32.0
21	Sivakumar et al. [52]	5	10, 20, 30, 40, 50	42.1	26.6-38.2
22	Ahmed and Vidyadhara [53]	5	20, 40, 60, 80, 100	36.7	21.9-29.4
23	Manzi et al. [54]	1	27	51.6	64.2
24	Shah et al. [55]	3	33, 50, 66	20.3	13.0-17.1
25	Kang et al. [56]	5	15, 30, 50	48.3-80.6	36.3-74.3
26	Xiao et al. [57]	4	30, 50, 70, 100	35.9	26.7-34.1

27	Chen et al. [58]	10	10, 20, 30, 40, 50, 60, 70, 80, 90,100	45.3	44.6-49.2
28	Corinaldesi [59]	5	100	43.9-58.6	34.7-46.1
29	Cabo et al. [60]	3	20, 50, 100	56.6	59.1-68.5
30	Adnan et al. [61]	12	25, 50, 75, 100	30.2-56.6	14.5-43.2
31	Exteberria et al. [62]	1	25	52.5	52.5
32	Poon et al. [63]	4	20, 50, 80,100	43.3	37.1-45.3
33	Surya et al. [64]	3	50, 75, 100	45.6	46.6-48.9
	Total	160	10-100	20.3-80.6	13.0-74.3

Table 7 Details of test data for splitting tensile strength of concrete containing CCA

Sl. No.	Reference	No. of datasets	r (%)	f_t (MPa)	f_{te} (MPa)
1	Present Study	27	25, 50, 100	3.5-5.7	3.0-5.2
2	Rao et al. [2]	3	25, 50, 100	2.7	2.0-2.3
3	Exteberria et al. [3]	1	25	2.7	3.0
4	Saravanakumar and Dhinakaran [20]	3	25, 50, 100	4.9	3.2-4.1
5	Fonteboa et al. [31]	6	20, 50, 100	2.8-2.9	2.4-3.1
6	Dimtriou et al. [39]	2	50, 100	4.2	3.1
7	Fursule and Shingade [40]	4	20, 30, 40, 50	2.6	1.8-2.3
8	Kou et al. [41]	6	20, 50, 100	3.3-3.4	2.8-3.2
9	Nirmaljeet and Vikram [42]	6	50, 100	3.1-3.5	3.0-3.5
10	Kabir et al. [44]	1	100	3.2	2.3
11	Abdel-Hey [47]	3	25, 50, 100	2.8	2.6-3.2
12	Seo and Lee [49]	2	100	2.9-3.4	2.6-3.1
13	Pepe et al. [50]	1	100	3.9	3.4
14	Ahmed and Vidyadhara [53]	5	20, 40, 60, 80, 100	3.2	1.9-2.9
15	Manzi et al. [54]	1	27	3.8	3.2
16	Kang et al. [56]	3	15, 30, 50	3.3	2.7-3.0
17	Exteberria et al. [62]	1	25	2.8	3.0
18	Surya et al. [64]	3	50, 75, 100	3.5	3.1-3.7
19	Liu et al. [65]	12	10, 20, 30	2.8	1.7-2.6
20	Sonawane and Pimplikar [66]	6	10,20, 30	5.0-5.8	4.3-5.6
21	Pereira et al. [67]	4	10, 30, 50, 100	2.9	2.5-2.9
22	Zega and Maio [68]	3	25, 50, 75	3.2	2.9-3.1
Total		103	10-100	2.6-5.8	1.7-5.6

Table 8 Details of test data for flexural strength of concrete containing CCA

Sl. No.	Reference	No. of datasets	r (%)	f_r (MPa)	f_{re} (MPa)
1	Present Study	27	25, 50, 100	3.9-5.9	3.4-5.7
2	Rao et al. [2]	3	25, 50, 100	5.2	4.2-5.0
3	Verma and Ashish [13]	10	10, 20, 30, 40, 50, 60, 70, 80, 90,100	4.2	3.4-4.3
4	Limbachiya et al. [19]	9	30, 100	5.2-7.0	4.9-7.2
5	Dimtriou et al. [39]	2	50, 100	8.6	6.6-7.4
6	Fursule and Shingade [40]	4	20, 30, 40, 50	3.8	3.2-4.0
7	Arora and Singh [43]	1	100	5.1	4.5
8	Kabir et al. [44]	1	100	4.3	3.5
9	Gumede and Franklin [48]	5	20, 40, 60, 80, 100	6.2	3.2-6.0
10	Ahmed and Vidyadhara [53]	5	20, 40, 60, 80, 100	4.1	2.3-3.7
11	Manzi et al. [54]	1	27	6.4	5.8
12	Chen et al. [58]	10	10, 20, 30, 40, 50, 60, 70, 80, 90,100	5.5	5.1-6.1
13	Liu et al. [65]	12	10, 20, 30	3.3	2.0-3.2
14	Manjunath and Prakash [69]	14	10, 20, 30, 40, 50, 80, 100	4.9-5.7	3.6-5.6
	Total	104	10-100	3.3-8.6	2.0-7.4

Table 9 Details of test data for modulus of elasticity of concrete containing CCA

Sl. No.	Reference	No. of datasets	r (%)	E_c (MPa)	E_{ce} (MPa)
1	Present Study	27	25, 50, 100	32355-38510	22840-37415
2	Rao et al. [2]	3	100	31220	20350-23570
3	Exteberria et al. [3]	1	25	32129	32840
4	Hamad and Dawi [14]	10	20, 40, 60, 80,100	32264-41944	27749-38908
5	Rahal [18]	5	100	11400-17800	11300-14900
6	Limbachiya et al. [19]	9	30, 50, 100	27000-30000	26500-31000
7	Fonteboa et al. [31]	6	20, 50, 100	29569	23994-28817
8	Dimtriou et al. [39]	2	50, 100	27300	20100-25400
9	Kou et al. [41]	6	20, 50, 100	30000-38700	21700-29100
10	Seo and Lee [49]	2	100	27700-31500	24600-28300
11	Pepe et al. [50]	1	100	24860	24770
12	Ahmed and Vidyadhara [53]	5	20, 40, 60, 80, 100	27816	23420-27092
13	Manzi et al. [54]	1	27	31400	30300
14	Corinaldesi [59]	4	20, 50, 100	33900-37300	22900-33300
15	Cabo et al. [60]	3	100	33308	30337-33516
16	Exteberria et al. [62]	1	25	33700	33200
17	Surya et al. [64]	3	50, 75, 100	28550	19380-24070
18	Liu et al. [65]	12	10, 20, 30	28000	21000-26000
19	Pereira et al. [67]	4	10, 30, 50, 100	34400	29900-33700
20	Cui et al. [70]	1	100	35600	22000
	Total	106	10-100	11400-41944	11300-38908

Table 10 Prediction models for CCA concrete

Sl. No.	Strength parameter	No. of Data sets	Model ($0< r \leq 1.0$)	R^2	Predicted/Experimental	
					Mean	SD
1.	Compressive strength	160	$f_{cp} = f_c^{0.95} r^{-0.07}$	0.998	1.02	0.19
2.	Splitting tensile strength	103	$f_{tp} = f_t^{0.89} r^{-0.02}$	0.987	1.02	0.15
3.	Modulus of rupture	104	$f_{rp} = f_r^{0.91} r^{-0.03}$	0.998	1.02	0.16
4.	Modulus of elasticity	106	$E_{cp} = E_c^{0.98} r^{-0.08}$	0.999	1.00	0.13

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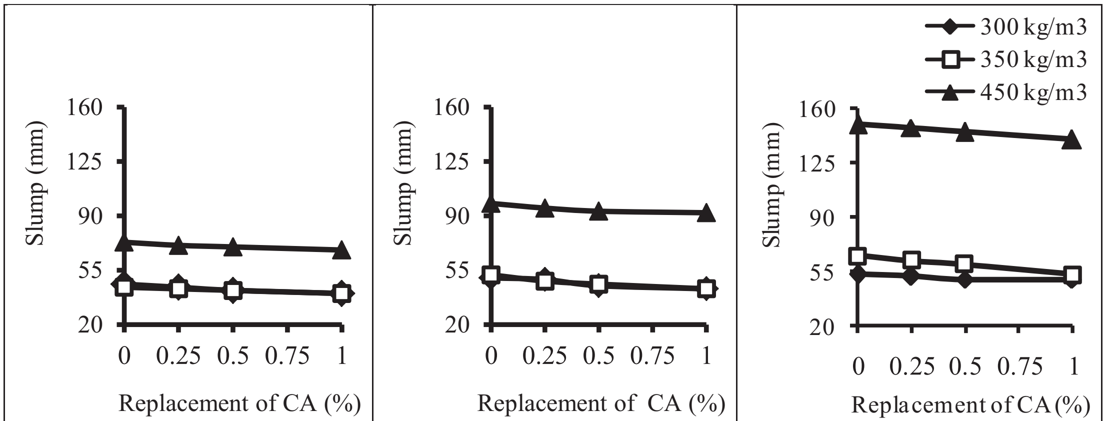
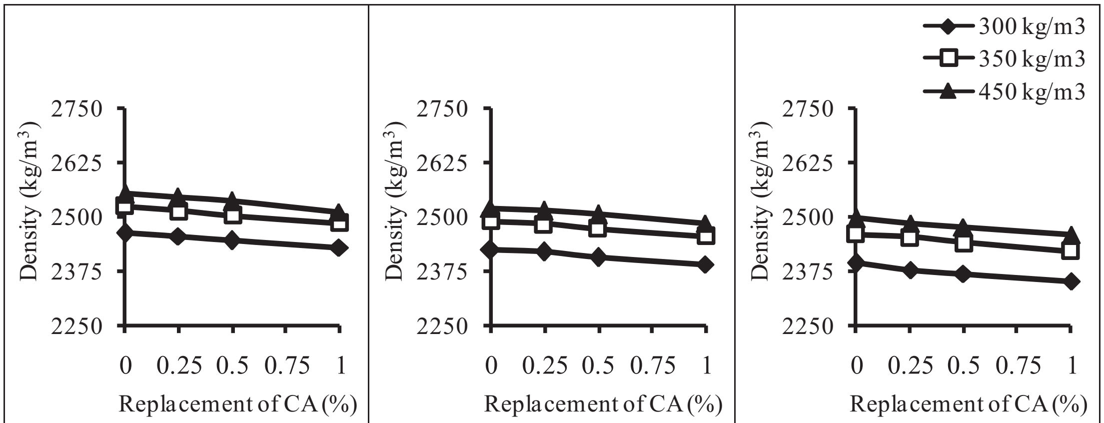


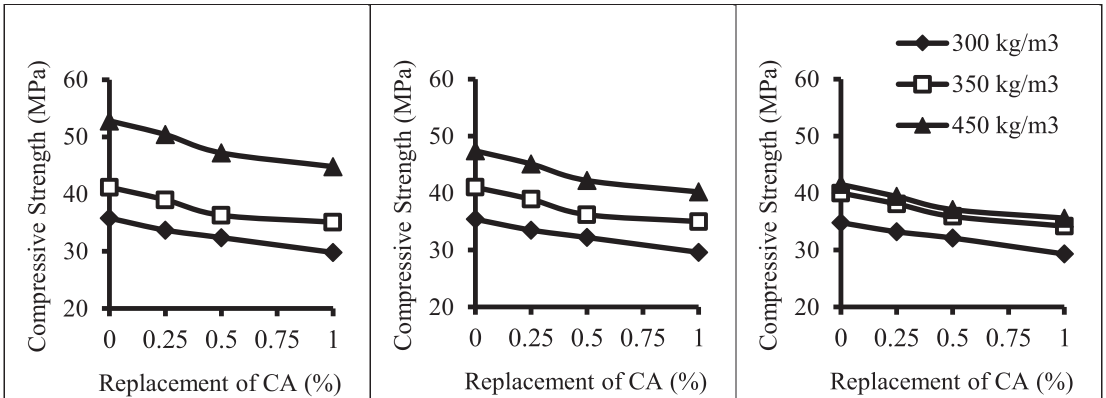
(a) w/c = 0.40 | (b) w/c = 0.45 | (c) w/c = 0.50

Fig. 1 Variation of workability due to addition of RCA



(a) w/c = 0.40	(b) w/c = 0.45	(c) w/c = 0.50

Fig. 2 Effect of aggregate replacement on density of concrete



(a) w/c = 0.40	(b) w/c = 0.45	(c) w/c = 0.50

Fig. 3 Effect of aggregate replacement on compressive strength of concrete

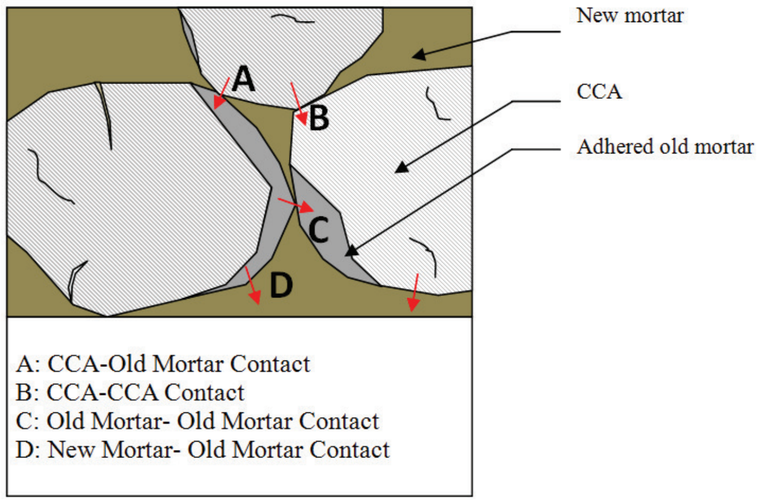
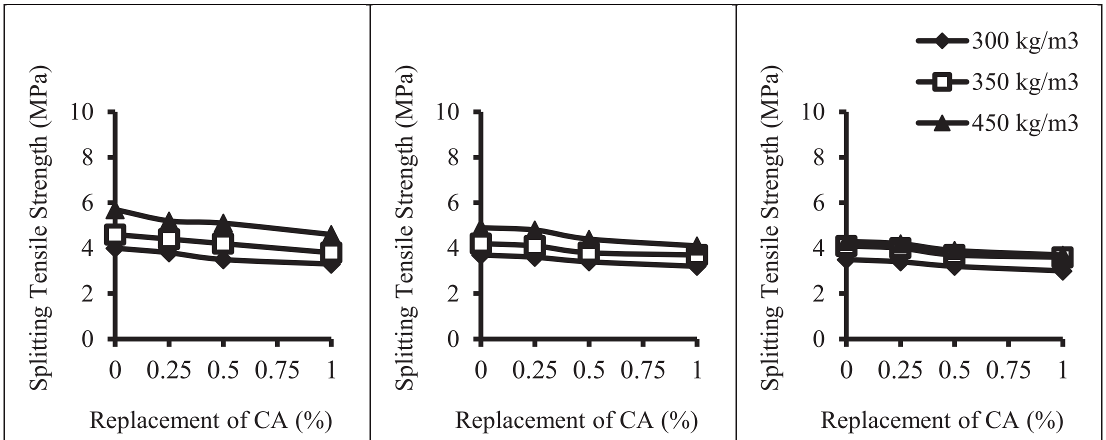
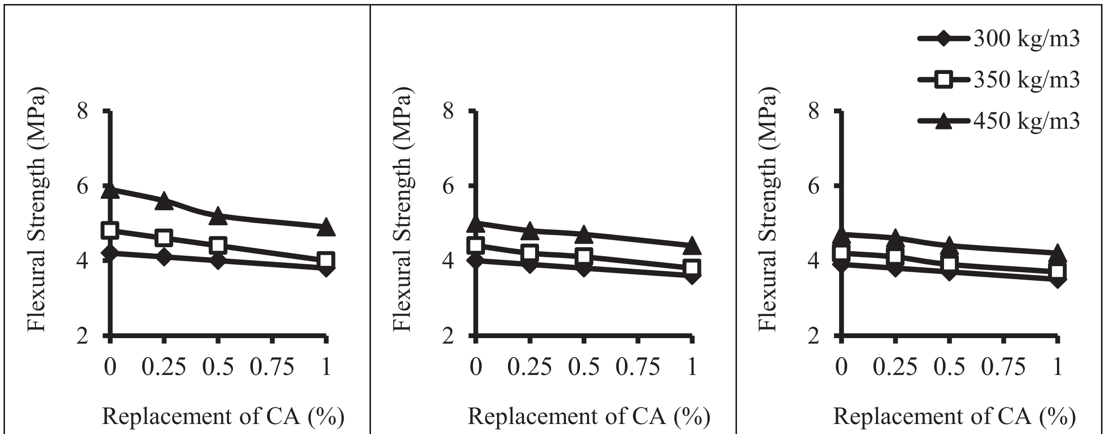


Fig. 4 Load transfer mechanism in CCA concrete



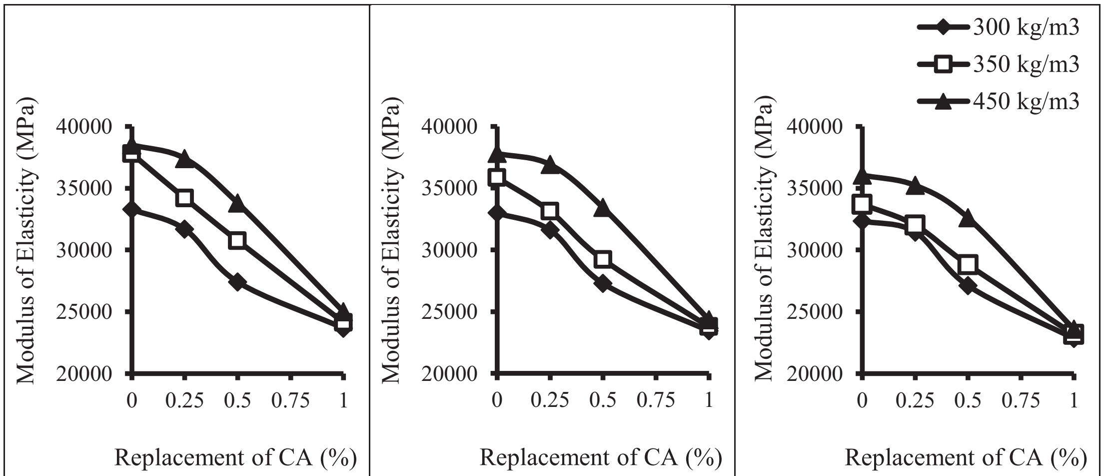
(a) w/c = 0.40	(b) w/c = 0.45	(c) w/c = 0.50

Fig. 5 Effect of aggregate replacement on splitting tensile strength of concrete



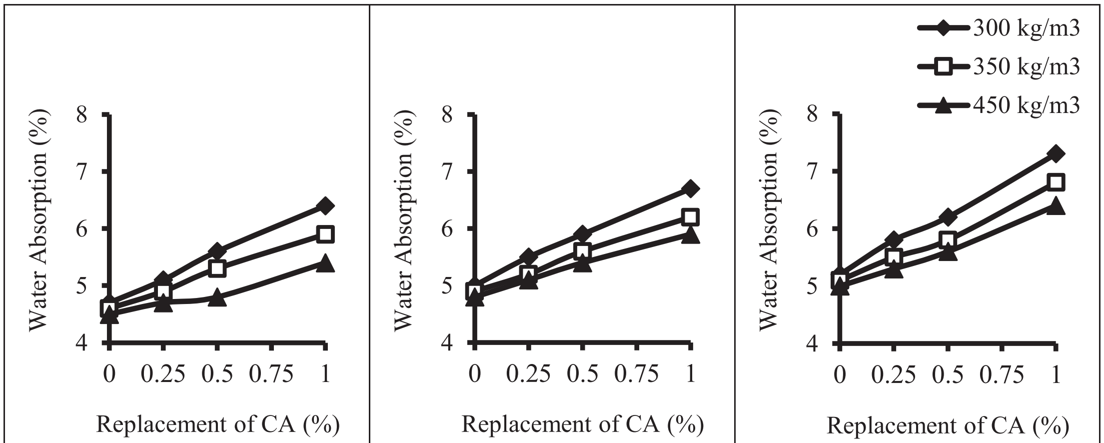
(a) w/c = 0.40	(b) w/c = 0.45	(c) w/c = 0.50

Fig. 6 Effect of aggregate replacement on flexural strength of concrete



(a) w/c = 0.40	(b) w/c = 0.45	(c) w/c = 0.50

Fig.7 Effect of aggregate replacement on modulus of elasticity of concrete



(a) w/c = 0.40	(b) w/c = 0.45	(c) w/c = 0.50

Fig. 8 Effect of aggregate replacement on water absorption of concrete

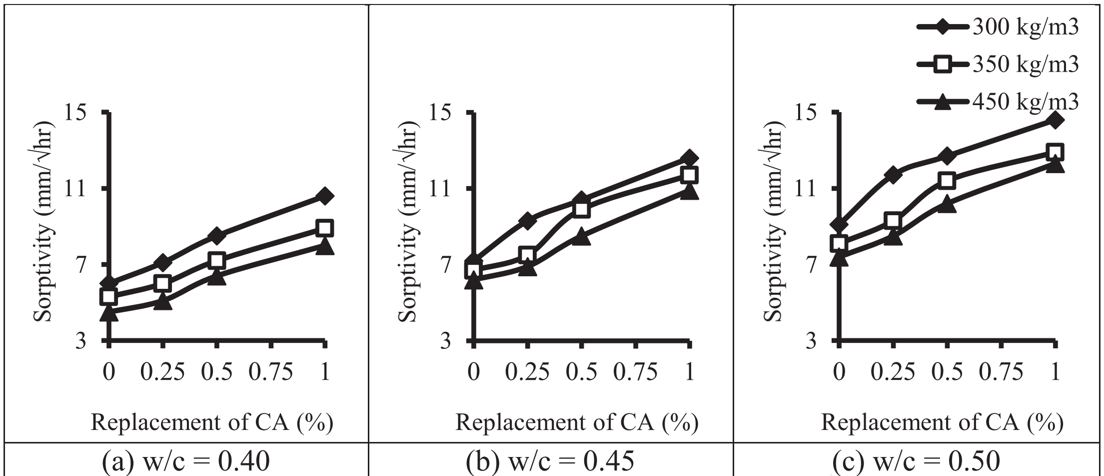
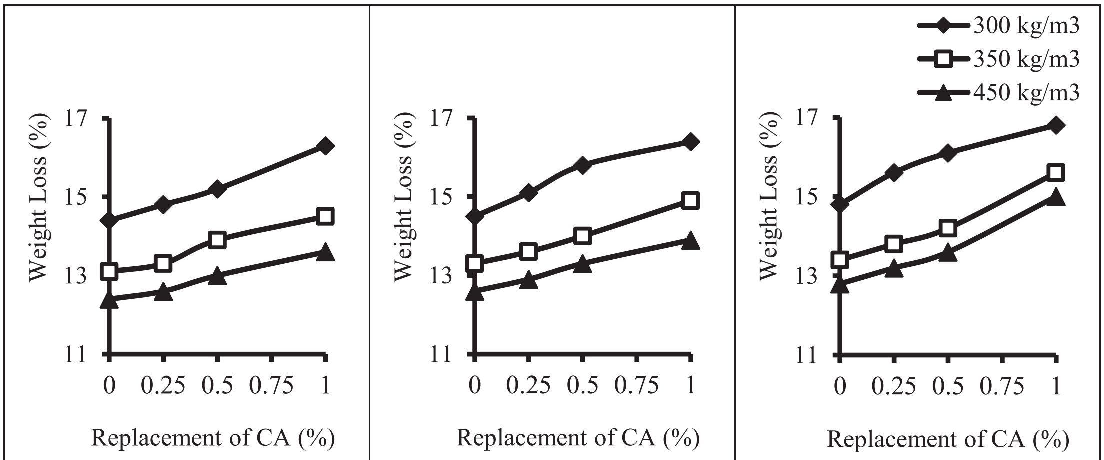
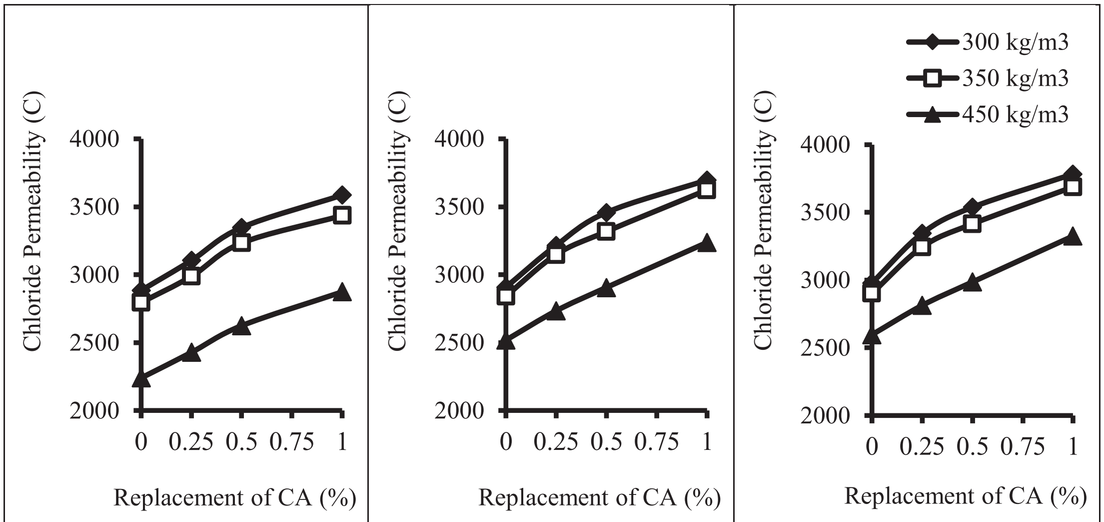


Fig. 9 Effect of aggregate replacement on sorptivity of concrete



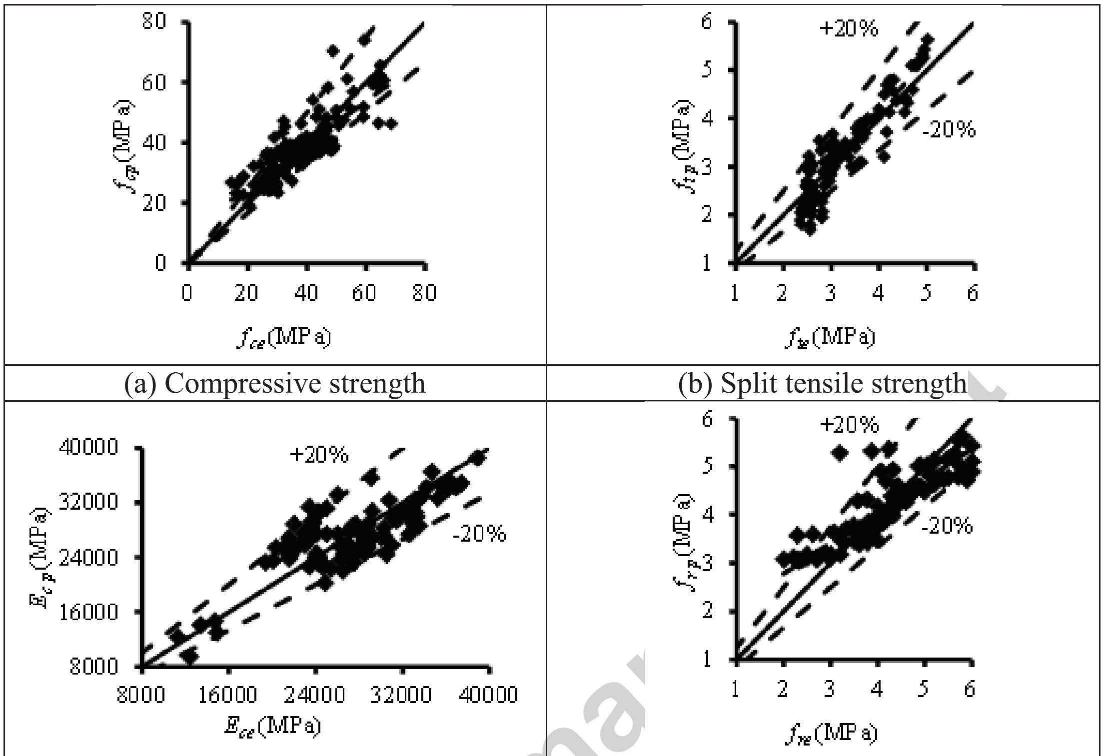
(a) w/c = 0.40 | (b) w/c = 0.45 | (c) w/c = 0.50

Fig. 10 Effect of aggregate replacement on acid resistance of concrete



(a) w/c = 0.40 (b) w/c = 0.45 (c) w/c = 0.50

Fig. 11 Effect of aggregate replacement on chloride permeability of concrete



(a) Compressive strength

(b) Split tensile strength

(c) Modulus of elasticity

(d) Flexural strength

Fig. 12 Comparison of predicted vs. experimental strength parameter value

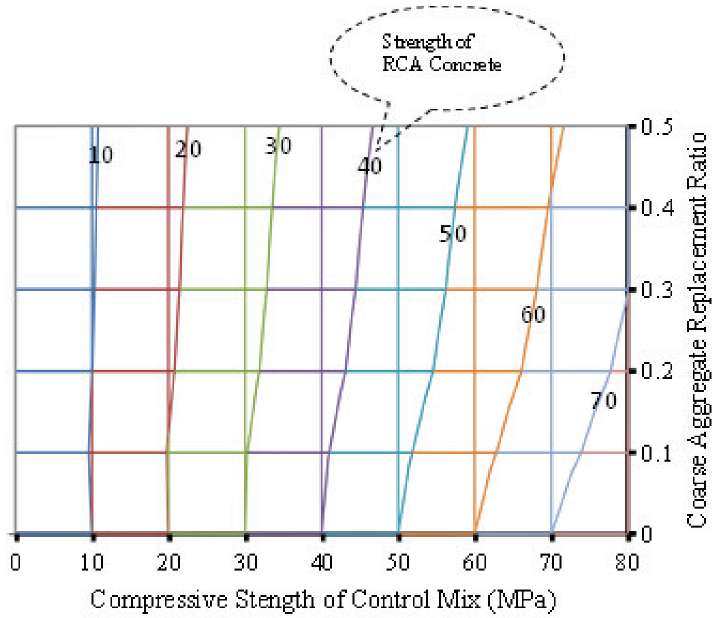


Fig. 13 Nomogram for the selection of strength grade of control mix

Highlights

- Conducted strength and durability tests on RCA concrete specimens corresponding to 36 mixes.
- Test variables include aggregate replacement percentage, water cement ratio, cement content of mix.
- Developed prediction models for compressive strength, splitting tensile strength, modulus of elasticity and flexural strength.
- Database for model development includes 469 test results with 81 from results from the present study and 388 from published literature.
- A nomogram for mix design of RCA concrete based on the prediction models is proposed.