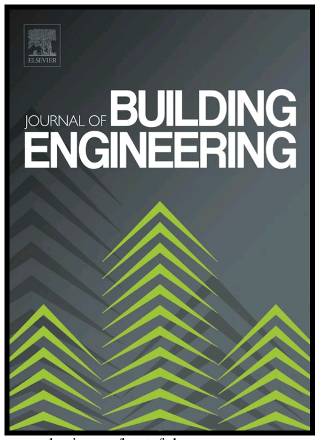

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STRENGTH AND DURABILITY OF CONCRETE CONTAINING CRUSHED CONCRETE AGGREGATES

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Abstract

Crushed concrete aggregates sourced from waste concrete are a sustainable alternative to natural crushed stone aggregates. This paper presents a study to evaluate the potential of replacing natural crushed stone aggregates in concrete with crushed concrete aggregates (CCA). Mathematical models were developed using regression analysis to account for the effect of aggregate replacement on the strength parameters of concrete. The strength and durability properties of concrete containing CCA were evaluated by a comprehensive experimental investigation involving nine control mixes. The variables considered in the experimental study are water cement ratio, cement content in concrete and percentage replacement of coarse aggregate (CA). The strength properties such as compressive strength, modulus of elasticity, split tensile strength and flexural strength are studied. The results obtained from the present study and data available in published literature were used for the development of the strength prediction models. Durability properties such as water absorption, sorptivity, acid attack resistance and chloride permeability are determined in this study. The test results showed that up to 25% of natural crushed stone aggregates in concrete may be replaced with CCA without significantly affecting the strength of concrete and that the partial replacement of natural aggregates with CCA can be recommended in areas of moderate exposure conditions. The mathematical models developed in this study can be used for the a priori prediction of the strength parameters satisfactorily. These models serve as simple tools to estimate the strength of concrete with different levels of aggregate replacement using CCA and can be used as design data of CCA concrete in structural members. A mix design methodology has been proposed using the models developed to aid the practicing engineers to arrive at the mix proportions of CCA concrete.

Keywords: crushed concrete aggregate; recycled aggregate concrete; strength; durability; prediction models

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1. Introduction

Coarse aggregates (CA) occupy the major share of concrete with respect to its volume. Several countries are currently facing shortage of natural aggregates and rely on imports to meet their demands. Rapid development and necessity for large scale infrastructure have resulted in indiscriminate and exploitation of natural rocks to meet the soaring demand for aggregates. Unplanned quarrying results in severe environmental degradation and also releases huge quantities of dust into the surroundings. Vibrations, pollution of air and water sources and landslides are some other impacts of unplanned quarrying. This calls for the adoption of greener construction technologies employing the use of artificial aggregates or recycled aggregates. Crushed concrete aggregates (CCA) are recycled aggregates obtained by crushing concrete waste from demolition sites, rejected precast members, laboratory specimens etc. Much of the construction and demolition wastes generated in India are currently dumped in landfills or low lying areas. Hence, utilization of crushed concrete aggregates derived from concrete waste is a value addition process and an eco-friendly alternative approach. The Indian Standard IS: 383 [1] permits the use of up to 20% recycled concrete aggregates in reinforced concrete constructions of grade M25 and below. The primary objective of this study is to identify the maximum aggregate replacement percentage for obtaining a strong and durable CCA concrete and to develop prediction models to estimate the strength parameters of CCA concrete. The influence of the variables on nine control concrete mixes was studied. The novelty in this paper is the development of empirical models to predict the mechanical properties of CCA concrete based on a wide range of test data and the detailed investigation on the durability properties of CCA concrete. The usefulness of the proposed prediction models in the mix design of the concrete containing CCA aggregate is discussed in this paper.

2. Background Information

Crushed concrete aggregates are considered to be a good substitute for the virgin aggregates in concrete production. Concrete waste from demolition sites has to be crushed to obtain CCA of the required gradation. Crushed concrete aggregates can be produced by primary crushing or by primary crushing together with secondary crushing of concrete waste. From an economical point of view, a single crushing process is generally preferred [2]. Crushed concrete aggregates are mainly composed of the original natural aggregates used for preparing the parent concrete and the cement mortar of the original mix adhered to its surface. The properties of concrete containing CCA depend largely on the mortar content of CCA which in turn depends on the strength of the original concrete from which the CCA are recycled. Exteberria et al. [3] suggested that the amount of adhered mortar on CCA depends on the crushing process and the water/cement ratio of the parent concrete. The proportion of mortar attached to the surface of CCA can be reduced by crushing CCA to a size closer to that of the natural crushed stone aggregates in the parent concrete [4]. The original concrete characteristics, the recycling process and the size fraction of aggregates are the three most important factors determining the properties of recycled concrete aggregates [5].

The replacement of natural aggregates in a concrete mix can be done either by weight or by volume. Knaack and Kurama [6] suggested that the variation in slump is insignificant when aggregates in concrete are replaced with CCA by volume. Fathifazl et al. [7] proposed that replacement of residual mortar in CCA concrete with equivalent fresh mortar yields concrete with almost the same strength as that of the control mix.

Zhao et al. [8] suggested three methods for mixing water to make CCA concrete; namely: pre-wetting of aggregates and adjusting for equivalent mixing water, pre-wetting without adjusting mixing water and adding extra water to account for aggregate absorption. It was observed that aggregates which were subjected to pre-wetting to the saturated surface dry condition produced concrete having better properties.

Water absorption of aggregate is an important factor affecting the strength of CCA concrete [9]. The presence of adhered mortar on the surface of CCA has a direct effect on the water absorption characteristics of CCA. McNeil and Kang [10] reported that the limit prescribed for the percentage of water absorption by recycled concrete aggregates varies in different international codes. IS: 383 [1] permits the use of CCA aggregates having water absorption less than of 10% and also suggests that the aggregates are to be pre-wetted to saturation before batching and mixing.

The density of CCA concrete is another important parameter that needs to be studied along with the water absorption and is directly related to the proportion of adhered mortar on the surface of CCA. McNeil and Kang [10] described that the density of mortar adhered to the surface of the recycled concrete aggregate is lesser than the original natural aggregate of equal volume and hence, this results in CCA concrete of a lower density. Rao et al. [2] established that the relationship between compressive strength and density of CCA concrete is linear. It was reported that the decrease in density of CCA concrete was found to be between 4-10% lower than the corresponding data of the control mix containing 100% natural aggregates.

Pedro et al. [11] reported loss of workability and density of concrete when natural aggregates in concrete were replaced with recycled concrete aggregates. Somna et al. [12] observed the slump of fresh CCA concrete can be maintained between 50 and 100 mm without the use of super plasticizers.

Verma and Ashish [13] studied the compressive strength and flexural strength of concrete made with successively recycled concrete aggregates. It was reported that the properties of concrete improved slightly for the lower levels of aggregate replacement. However, the properties of concrete were badly affected when more than 50% of the natural aggregates were replaced. Hamad and Dawi [14] prepared crushed concrete from normal strength concrete and high strength concrete and the average reduction in the mechanical properties of concrete containing CCA was found to be 10%. Saha and Rajasekaran [15] conducted experimental investigations to determine the strength characteristics of concrete produced with Portland Pozzolana Cement and recycled concrete aggregates. The compressive strength, splitting tensile strength and flexural strength of concrete were found to decrease significantly with the addition of recycled coarse aggregates. Silva et al. [16] observed that the tensile strength of CCA concrete can be controlled by careful selection of aggregates before manufacturing the concrete. Tabsh et al. [17] identified that the strength of high grade CCA concrete of the order of 50 MPa is not affected by the replacement with recycled aggregates and there is significant loss on the strength of ordinary concrete when CCA was used. Exteberria et al. [3] noted that the 28-day strength of concrete containing 100% CCA is 20-25% lower than the strength of the corresponding conventional concrete mix. It was also reported that the mechanical properties of medium strength concrete using 25% CCA are not affected if the quantity of cement remains the same and if an equal effective water cement ratio is maintained. Rahal [18] studied the mechanical properties of concrete containing CCA and reported that only 3% reduction was seen in the modulus of elasticity of concrete containing recycled aggregates. Limbachiya et al. [19] investigated the strength and durability properties of concrete made using crushed concrete aggregates obtained from rejected precast concrete members. The flexural strength and modulus of elasticity of concrete containing recycled aggregates were found to be similar to concrete made with natural aggregates. The durability characteristics, estimated using tests for air permeability, initial surface absorption, chloride diffusion, chloride induced corrosion, freeze thaw resistance and abrasion resistance of concrete containing recycled aggregates, were also found to be similar to that of normal concrete. It was concluded that up to 30% replacement of aggregates did not affect the strength characteristics of concrete.

Saravanakumar and Dhinakaran [20] studied the durability characteristics of recycled aggregate concrete with respect to its resistance to chloride ion penetration, sorptivity and acid attack resistance. It was concluded that the durability of concrete decreases with addition of recycled concrete aggregates. The results of Rapid Chloride Permeability Test (RCPT) indicated that the chloride permeability was found to be 'Moderate' as per ASTM C1202 [21] when CCA was used in concrete. Thomas et al. [22] investigated the durability of concrete containing recycled aggregates. It was reported that use of CCA resulted in concrete having intrinsic porosity and decreased the durability. Wang et al. [23] reported that the durability of CCA concrete can be improved by the addition of pozzolanic materials such as superfine phosphorus slag and ground granulated blast-furnace slag. It can be observed that the use of CCA in normal concrete has been studied extensively in the literature.

3. Experimental program

Strength and durability properties of concrete made with crushed concrete aggregates (CCA) were studied by an experimental investigation. The variables considered in the study are water-cement ratio, cement content and percentage of replacement of coarse aggregate (CA). Compressive strength, split tensile strength, modulus of elasticity and flexural strength are evaluated to study the influence of replacement of stone aggregates with crushed concrete aggregates in concrete. The durability properties such as water absorption, sorptivity, acid attack resistance and chloride permeability were also determined.

3.1 Material Characterization

Ordinary Portland Cement (OPC) conforming to IS: 12269 [24] was used in the study. The physical properties of cement were determined by laboratory tests and are reported in Table 1. Manufactured sand conforming to Zone II of IS: 383 (2016) [1] was used as fine aggregate. The physical properties of the fine aggregate are given in Table 2. Crushed stone aggregates (CSA) of maximum size 20 mm conforming to IS: 383 [1] were used as coarse aggregate. The specific gravity of natural stone aggregates was found to be 2.6.

Crushed concrete aggregate was produced from concrete waste sourced from the demolition site of a water tank. The core strength of the original concrete was found to be

25 MPa. The concrete waste collected was subjected to primary crushing and screened to control the particle sizes of the crushed concrete aggregate. The aggregate so obtained was water washed under pressure to remove any loose mortar and impurities. The aggregate sizes were proportioned to comply with the requirements of grading as per IS: 383 [2]. The water absorption of CCA was found to be 6.4%.

3.2 Mix Design

The design of concrete mixes was done by following the guidelines in IS: 10262 [25]. The ratio of volume of coarse aggregate to total aggregate volume was kept constant as 0.64. A total of 36 mixes were designed for various levels of aggregate replacement, water cement ratio and cement content. The water cement ratio was varied between 0.4 and 0.5 and the cement content was varied between 300 kg/m^3 and 450 kg/m^3. The control mixes contain crushed stone aggregates alone as coarse aggregates while the remaining mixes contain crushed concrete aggregates replacing the natural coarse aggregates. The levels of aggregate replacement considered in the study are 0%, 25%, 50% and 100% by volume. The mix was designated to include cement content, water cement ratio and aggregate replacement ratio. For example, the designation 350/0.5/0.25 represents a mix containing 350 kg/m^3 of cement, water cement ratio of 0.5 and aggregate replacement ratio of 0.25. The control mixes are designated as 300/0.4/0, 350/0.45/0 and 400/0.5/0. The crushed concrete aggregates were pre-wetted to the saturated surface dry condition before mixing. The quantity of water was adjusted for surface moisture of fine aggregate and water absorption of natural aggregate. The mix designations and the weight of constituent materials are given in Table 4. The constituent materials were weigh batched and mixed using a pan mixer to prepare the homogeneous fresh mix. The specimens were cast and removed from the moulds after 24 hours and all specimens were cured for 28 days by immersing in water. After curing, the specimens were taken out from the tank and the surfaces of the specimens were wiped before testing.

3.3 Testing

The workability of fresh concrete was determined using slump test [26]. The density of the control mixes and concrete containing CCA in the fresh state were also determined. To determine the properties of hardened concrete, three specimens were tested for each test and the average values were reported. The 28 day compressive strength of concrete specimens containing natural aggregates and specimens containing crushed concrete aggregates were determined by testing cubes of size 150 mm×150 mm ×150 mm as per IS:516 [27] in a compression testing machine of capacity 2000 kN. Split tensile strength and modulus of elasticity were determined by conducting tests on cylinder specimens of size 150 mm diameter and 300 mm height as per IS: 516 [27]. Flexural strength of concrete was determined by testing prismatic specimens of size 150 mm × 150 mm × 700 mm over a span of 600 mm according to IS: 516 [27]. The durability of concrete was determined by conducting tests to determine the water absorption, sorptivity, resistance to chloride penetration and resistance to acid attack. The water absorption was determined by weighing specimens with 100 mm diameter and 50 mm thickness in dry condition and wet condition. Sorptivity test was conducted as per ASTM C1585 [28] using disc shaped specimens of size 100 mm diameter and 50 mm thickness. Tests were conducted on cube specimens of size 150 mm × 150 mm × 150 mm to determine the mass loss on immersion in a 3% sulphuric acid solution over a period of 90 days. The surface colour change, surface deterioration, weight loss and strength loss were studied. The resistance to chloride penetration was determined by conducting RCPT on concrete specimens according to ASTM C1202 [21] on concrete disc specimens of size 100 mm diameter and 50 mm thickness. The total charge passing through the specimen was measured to find the resistance against chloride ion penetration. The test results of control mix containing CSA were compared with corresponding test data of mixes containing partial to full replacement with CCA.

4. Results and Discussion

The effect of percentage of aggregate replacement on the strength and durability properties of CCA concrete was determined. The properties of workability and density were determined in the fresh state. The properties of hardened concrete such as compressive strength, splitting tensile strength, modulus of elasticity, flexural strength, water absorption, sorptivity, acid attack resistance and resistance to chloride permeability were also determined.

4.1 Workability

The workability of concrete was determined by conducting slump test and is given by Fig. 1. The influence of water cement ratio on the workability of the mix is given in Fig. 1(a) – 1(c). The workability of concrete decreases with the increase in percentage of natural aggregates replaced. The crushed concrete aggregate consists of rock pieces from parent concrete and partly adhered mortar used in the parent concrete. The old adhered mortar layer on the surface of CCA causes greater internal friction inside the fresh mix.

This causes reduction in the workability of CCA concrete with the increase in replacement ratio of coarse aggregate. The workability for a mix with water cement ratio w/c = 0.50 is significantly higher than that of a mix with w/c = 0.4. The water content of the concrete mix increases with the increase in water cement ratio when the cement content remains the same. This is the reason for mixes having higher w/c ratio exhibiting higher workability. Similarly, for the same water cement ratio, the water content increases with the increase in cement content. The increase in water content in the mix contributes towards the increase in workability. Hence, the workability of concrete increased with the increase in cement content for the same water cement ratio..

4.2 Fresh density

The density of concrete is found to decrease with the increase in replacement ratio of coarse aggregate and is shown in Fig. 2. The bulk density of the crushed concrete aggregate (CCA) is lower than the virgin aggregate because of the presence of the old mortar adhered to its surface. Hence, concrete containing CCA has lower density when compared to the corresponding mixes containing CSA.

The density of concrete is found to decrease with the increase in water cement ratio of the mix. With the increase in water cement ratio of mixes with the same cement content, the water content also increases. The constituent of concrete having the lowest density is water and hence, concrete with higher water content will have lower density.

Similarly, for the same w/c, the fresh density of concrete is found to increase with the increase in the cement content of the mix. As the cement content in the mix increases there is a corresponding reduction in the water content of the mix. As, the density of cement is greater than water, the density of concrete also increases.

4.3 Compressive strength

The variation of cube compressive strength of concrete due to the addition of CCA is given in Fig. 3. The reduction in the compressive strength is minimal (1.5%-5%) when 25% of the natural aggregates are replaced by CCA. This indicates that no change in mix design procedure needs to be proposed while recommending a replacement of 25% CSA with CCA.

The compressive strength was found to decrease with the increase in replacement ratio of aggregates. The strength of the concrete composite is governed by the aggregate phase, mortar phase and interface between the mortar and the aggregates. Out of these, the aggregate phase is comparatively stronger than the other phases in both CSA concrete and CCA concrete and the quality of aggregates is an important factor affecting the strength of concrete. The interfacial transition zone is weaker in CCA concrete when compared to CSA concrete due to the presence of the old adhered mortar from the parent concrete. Xu et al. [29] reported that the strength of concrete containing CCA is lower than normal aggregate concrete owing to the micro-cracking of the old mortar adhered to the surface of CCA. The load transfer takes place either through the interfacial transition zone or through the direct contact points between the aggregates. Three types of interfacial transition zones exists in CCA concrete, namely, the zone between the aggregates and the new cement mortar, the zone between the old cement mortar and the new cement mortar and the zone within the CCA between aggregate and the old adhered mortar. The transition zone between the aggregate and the old adhered mortar is the generally the weakest amongst the three transition zones in CCA concrete [30]. Inherent micro cracks in the transition zone make it weaker and high stress concentration at the crack tips leads to the propagation of these micro cracks [31]. The presence of weaker transition zones in CCA concrete results in a concrete of lower strength when compared to the concrete containing natural aggregates. The direct contact points between the crushed concrete aggregates can be of three types. These are the contact points between aggregate and aggregate, aggregate and old mortar and between old mortar and old mortar. In ordinary concrete, the strongest link in the load transfer mechanism is the aggregate-aggregate contact surface and the weakest is generally the aggregate-mortar contact surface or the interfacial transition zone. In CCA concrete, additional types of contact surfaces for load transfer exist which include the aggregate-old mortar contact surface and the old mortar-old mortar contact surfaces as shown in Fig. 4. The load transfer mechanism in CCA concrete is therefore dependant on the properties of the contact surfaces existing between its various constituents.

A higher compressive strength was obtained for concrete having higher cement content at constant w/c ratio and aggregate replacement level. For the same water cement ratio (w/c), the colloidal binding paste increases in the mix when the cement content increases. This enhances the binding of the aggregate with the cement resulting in stronger interfaces and hence, the strength of concrete increases with increase in the cement content. The test results indicate that a high amount of cement is required for concrete containing 100% CCA to achieve strength equal to the control mix. The observations of the study corroborate with the findings of Exteberria et al. [3].

Maximum compressive strength was observed for concrete with the lowest water cement ratio and this corroborates with Abram's law. The maximum reduction in strength (18.9%) was observed for the mix 450/0.5/1 with 100% replacement of natural aggregates. The increase in water cement ratio is a reason for the loss of strength in this case.

4.4 Splitting tensile strength

The split tensile strength of concrete is found to decrease with the increase in the water cement ratio and the percentage replacement of aggregate and is shown in Fig 5. When the percentage of CCA in the mix was 25%, the reduction in the split tensile strength was found to be about 2-8%. With the increase in water content, the transition zone developed is of poorer quality and hence the strength obtained is lower. For the same water cement ratio, the splitting tensile strength of concrete increases with the increase in cement content. This may be attributed to a stronger interfacial transition zone and an improvement in the properties of the hydrated cement paste as a result of the increase in cement content. The reduction in tensile strength of concrete with addition of CCA may be attributed to the presence of porous mortar on the surface of recycled aggregates and increased water absorption at the surface of aggregates. The angularity in recycled aggregates compensates the reduction in strength to a certain extent by the formation of more number of mechanical bonds thereby minimizing the effect of the adhered porous mortar. Matias et al. [32] suggested that the use of super plasticizers helps to offset the reduction in splitting tensile strength with the increase in the percentage of aggregates replaced with CCA. Mukharjee and Barai [33] reported that this loss in tensile strength with addition of CCA in concrete can be minimized by the addition of nano-silica to the concrete mix. Nano-silica particles fill in the nano-sized pores and enhance the tensile strength by improving the bond between the recycled aggregates and the hydrated cement paste.

4.5 Flexural strength

The flexural strength or modulus of rupture of concrete also decreases with the increase in percentage of CCA and is given in Fig. 6. A decrease of 2-5% in the flexural strength can be observed for a replacement of 25% of natural aggregates in the mix. With the increase in percentage of CCA, a maximum reduction of 13% in the flexural strength was observed for the mix 450/0.5/1. The shape, surface texture, and modulus of elasticity of the aggregates are the main factors affecting the flexural strength of concrete. Kaplan [34] observed that the elastic properties of aggregates greatly influence the flexural strength of concrete. The lower modulus of elasticity of CCA resulted in the reduction of the flexural strength of concrete. Silva et al. [16] proposed that the transition zone between CCA and hydrated cement paste exhibits increased mechanical bonds due to the angular shape of CCA. The surface texture of CCA is rougher due to the presence of adhered mortar on its surface and this also influences the reduction in the flexural strength of CCA concrete. Safiuddin et al. [35] suggested that the larger dimension of CCA is generally oriented in the longitudinal direction of the prism specimen which helps to produce better bond with the surrounding mortar.

The flexural strength decreases with the increase in water cement ratio and increases with the increase in cement content of the mix. With the increase in cement content of the mix for the same water cement ratio, a denser paste and stronger transition zone is formed, which contributes to the improvement in flexural strength of concrete.

4.6 Modulus of elasticity

The modulus of elasticity of concrete was found to decrease with the increase in the percentage of CCA in the mix and is shown in Fig. 7. The modulus of elasticity was determined in the pre-cracking stage and hence, the presence of inherent micro cracks in the transition zone is responsible for the variation in the modulus of elasticity of concrete. The micro cracks formed within the CCA during the crushing process and also at the interface between the aggregate and the old mortar leads to the reduction of the stiffness of the composite system. This results in a lower modulus of elasticity in concrete containing CCA when compared to the concrete containing CSA. In the control mixes, the transition zone between the natural aggregates and the cement mortar is relatively stronger than the transition zone in CCA and hence exhibits better elastic properties. The maximum reduction in modulus of elasticity was observed for the mixes containing 100% CCA. With the increase in the percentage of CCA in the mix, the modulus of elasticity decreases due to the presence of a weaker transition zone between the recycled aggregates and the cement mortar. An average reduction of 5% in the modulus of elasticity was observed when 25% of the natural aggregates were replaced with CCA. Fathifazl et al. [7] proposed that the mortar attached to the surface of CCA behaves as aggregate phase in concrete before its hardening and becomes part of the mortar phase after hardening. Hence the total mortar proportion in CCA concrete becomes greater than the control mix and as a result, the modulus of elasticity obtained becomes lower than the control mix.

The modulus of elasticity was also found to decrease with the increase in the water cement ratio of the mixes. Brito and Robles [36] suggested that the presence of voids due to the excess water content after hydration reduces the stiffness of the mortar phase. This causes the reduction in the modulus of elasticity of concrete with the increase in the water cement ratio.

The presence of greater cement content helps to form stronger mortar phase in concrete which yields greater stiffness and this is the reason for the increase in modulus of elasticity with increase in cement content for mixes having the same water cement ratio.

4.7 Water absorption

Water absorption in CCA concrete increases with the increase in percentage of replacement of natural aggregates and is given in Fig 8. The water absorption by CCA is higher than CSA due to the presence of mortar from parent concrete adhered to its surface. Belin et al. [37] suggested that water absorption characteristics of CCA also depend upon the quality and quantity of the adhered mortar. With the increase in percentage of CCA in the mix, water absorption by the concrete also increases due to the presence of voids in the adhered old mortar. The porous paste structure of CCA concrete also increases the absorption of water by CCA concrete. It can be observed that the water absorption is lower for concrete with lower water cement ratio owing to the better quality of the hydrated cement paste. The hydrated paste content increases with the increase in cement content and a denser mortar paste is formed. This is the reason for the lower water absorption for mixes containing higher cement content.

4.8 Sorptivity

Capillary absorption increases with increase in percentage of replacement of CCA in the mix and can be inferred from Fig. 9. Mixes containing CCA show an increase in capillary absorption when compared to the control mixes. Belin et al. [37] found out that the absorption of water into the voids of crushed concrete aggregates and the porous mortar adhered to the surface of CCA by capillary action results in the increase of sorptivity. The increase in percentage of CCA in the mix also results in the formation of a porous paste structure and a poorer interfacial zone having higher permeability than the control mixes. The increase in capillary voids in the concrete microstructure with the addition of CCA in the mix results in higher absorption of water by capillary action. The capillary absorption was also found to increase with the increase in water cement ratio. When the water cement ratio in the mix increases, the paste formed is porous as a result of the localized bleeding at the interface of CCA and the fresh mortar paste. This results in the increase in absorption of water by capillary action with the increase in the water cement ratio. When the cement content in the mix increases, the gel-space ratio obtained is higher and denser hydration products are formed. This reduces the capillary percolation of water in concrete having higher cement content.

4.9 Acid resistance

The acid attack resistance is measured in terms of the loss of weight of specimen under the attack of sulphuric acid. A lower weight loss indicates higher acid resistance. The resistance to sulphuric acid decreases with the increase in percentage of aggregate replaced as seen from Fig. 10. Decalcification of the hydrated cement paste takes place during acid attack. This results in the production of reaction products of high volume. The factor determining the acid attack is the permeability in concrete which depends on the porosity, size of the pores, continuity of the pores and its distribution. Concrete containing

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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LIST OF TABLES

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 ($0< r \le 1.0$)	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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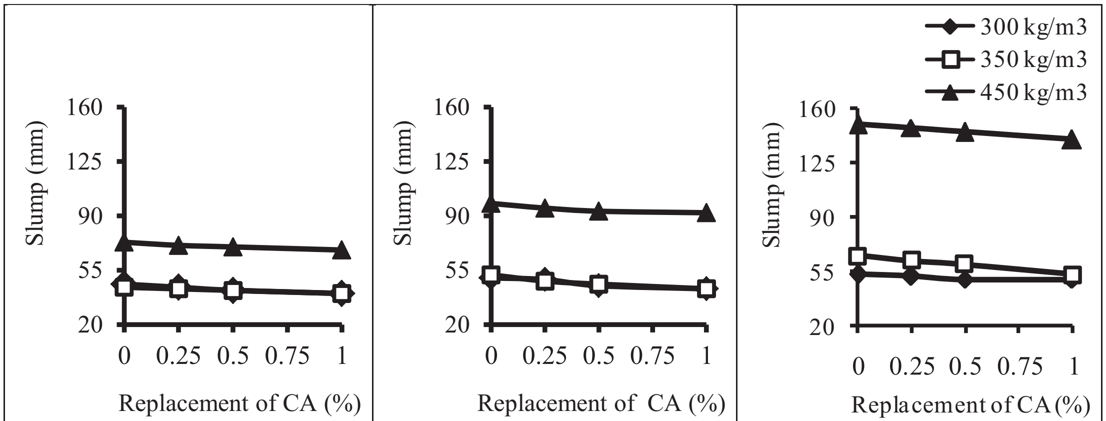
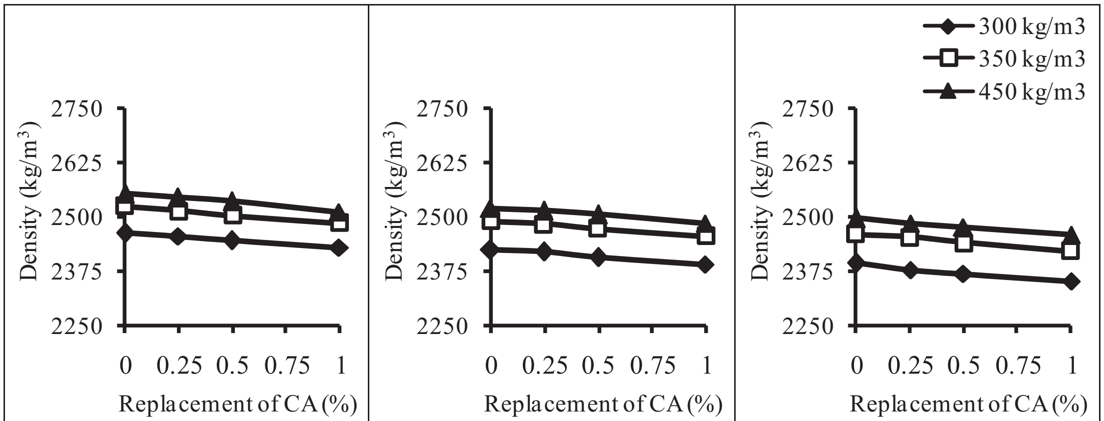


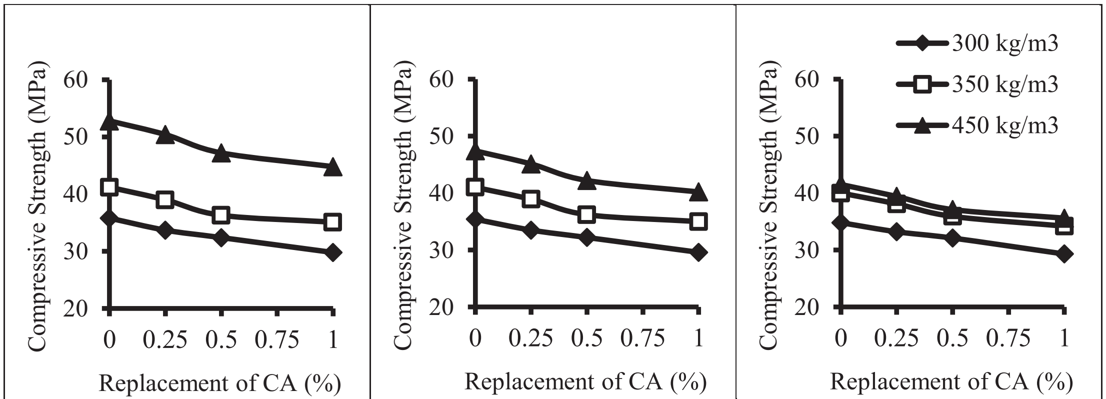
(a) w/c = 0.40	(b) w/c = 0.45	(c) w/c = 0.50

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

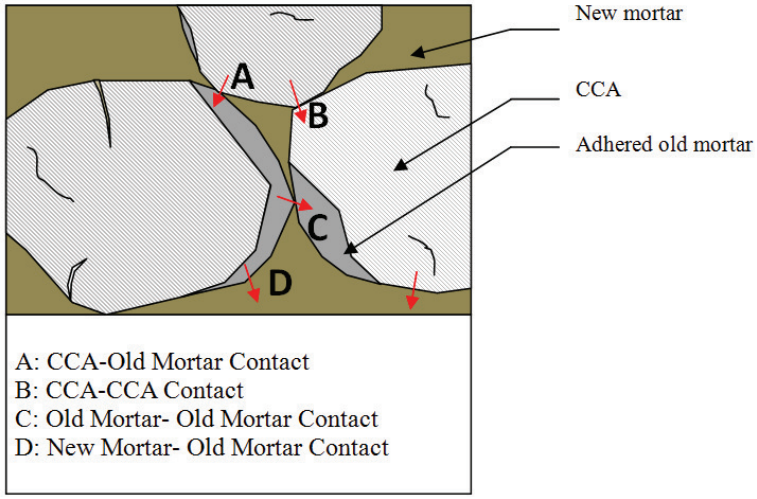
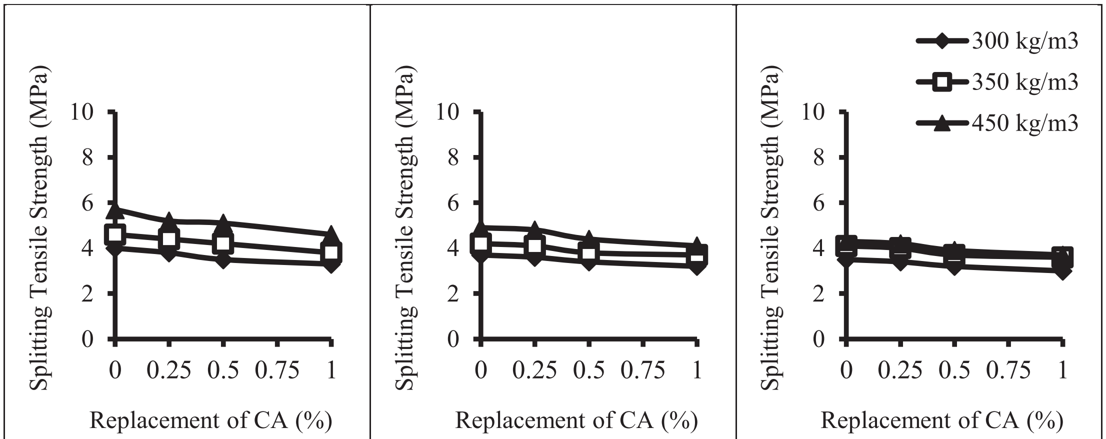
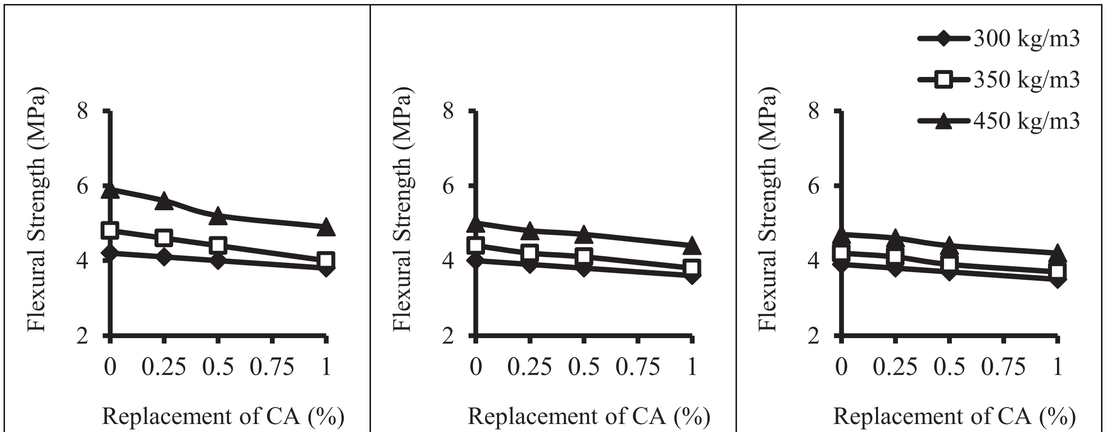


Fig. 4 Load transfer mechanism in CCA concrete



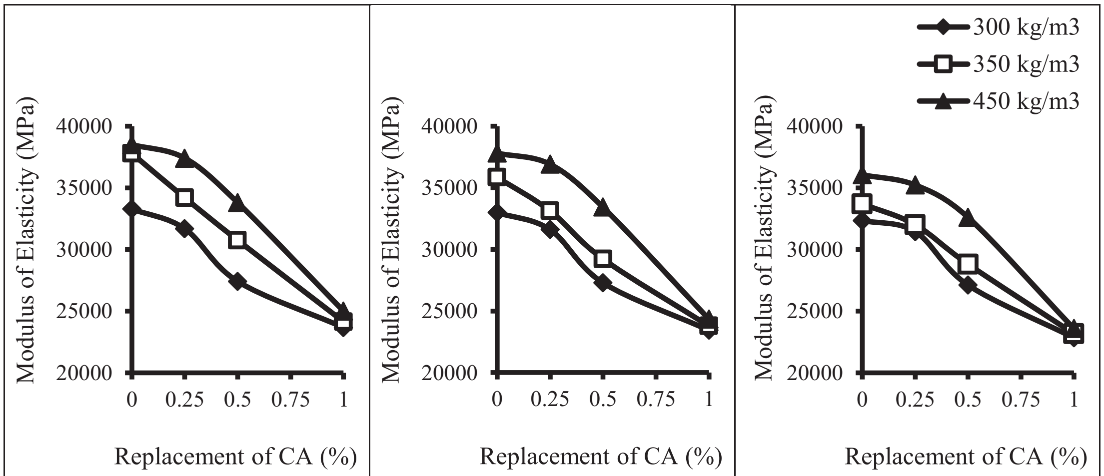
(a) w/c = 0.40 | (b) w/c = 0.45 | (c) w/c = 0.50

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

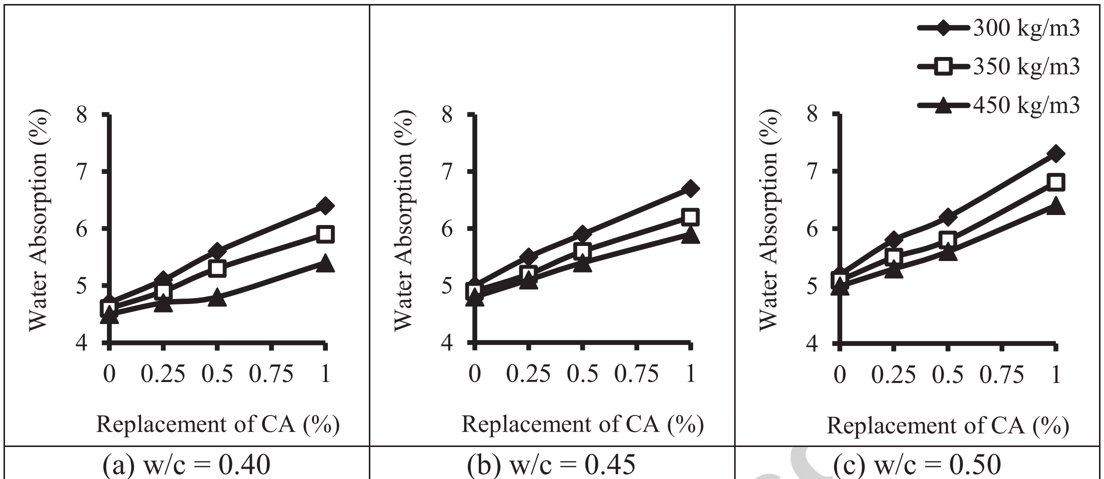
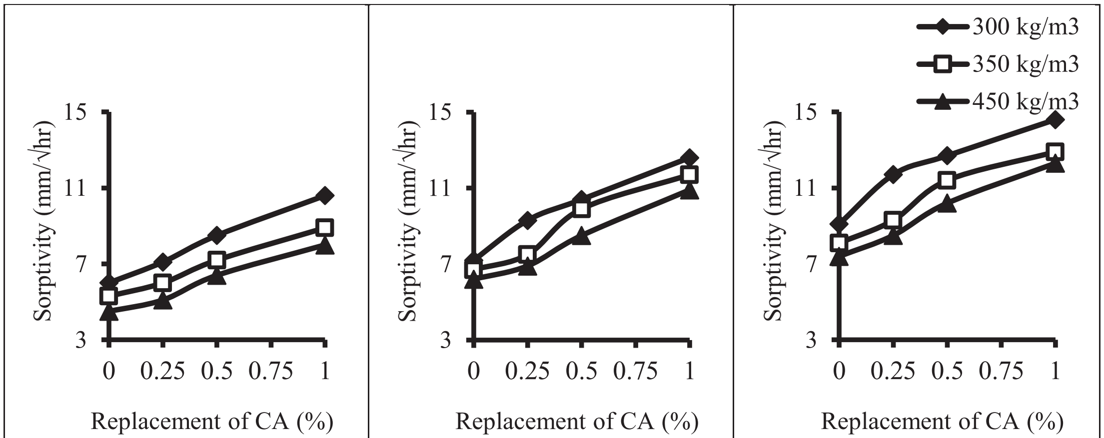
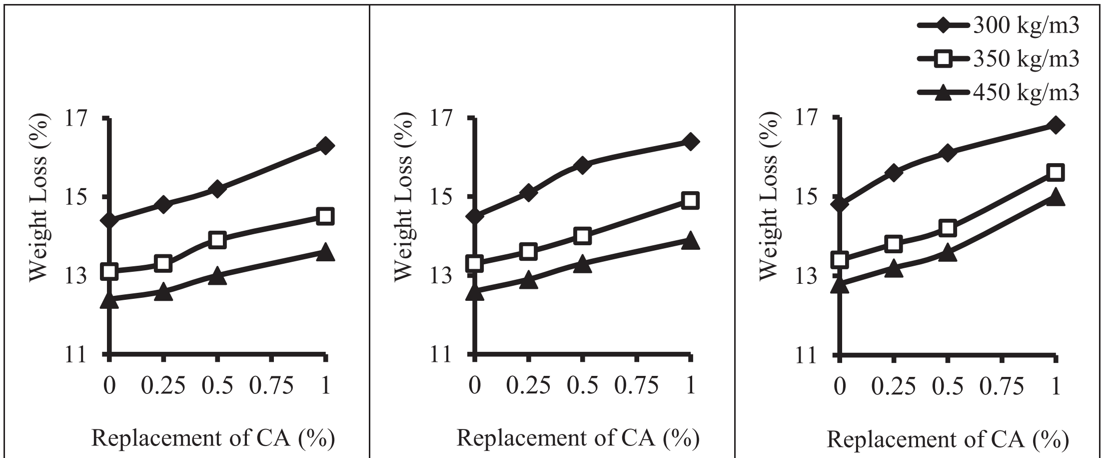


Fig. 8 Effect of aggregate replacement on water absorption of concrete



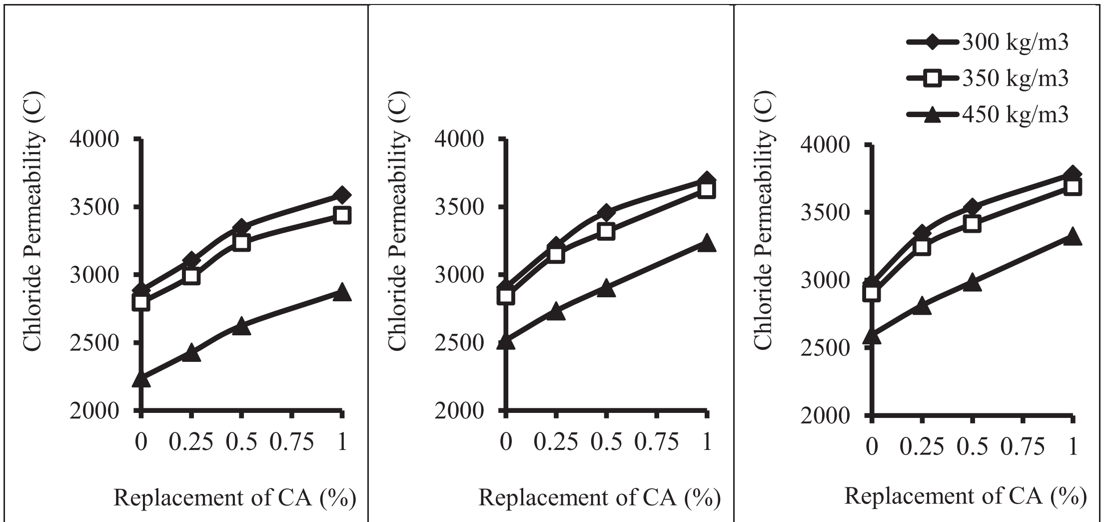
(a) w/c = 0.40	(b) w/c = 0.45	(c) w/c = 0.50

Fig. 9 Effect of aggregate replacement on sorptivity of concrete



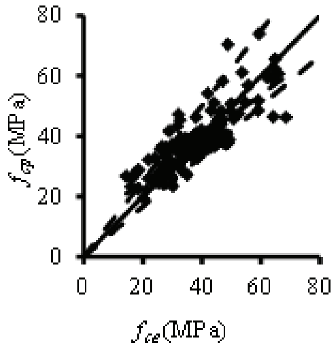
(a) w/c = 0.40	(b) w/c = 0.45	(c) w/c = 0.50

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

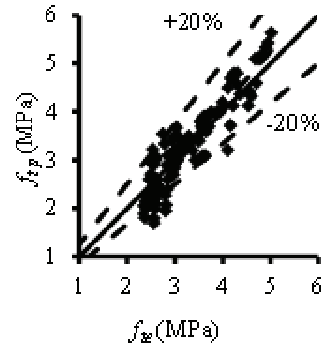


(a) w/c = 0.40	(b) w/c = 0.45	(c) w/c = 0.50

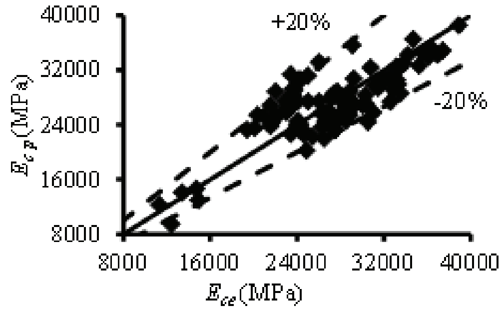
Fig. 11 Effect of aggregate replacement on chloride permeability of concrete



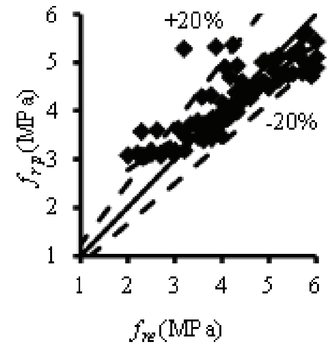
(a) Compressive strength



(b) Split tensile strength



(c) Modulus of elasticity



(d) Flexural strength

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

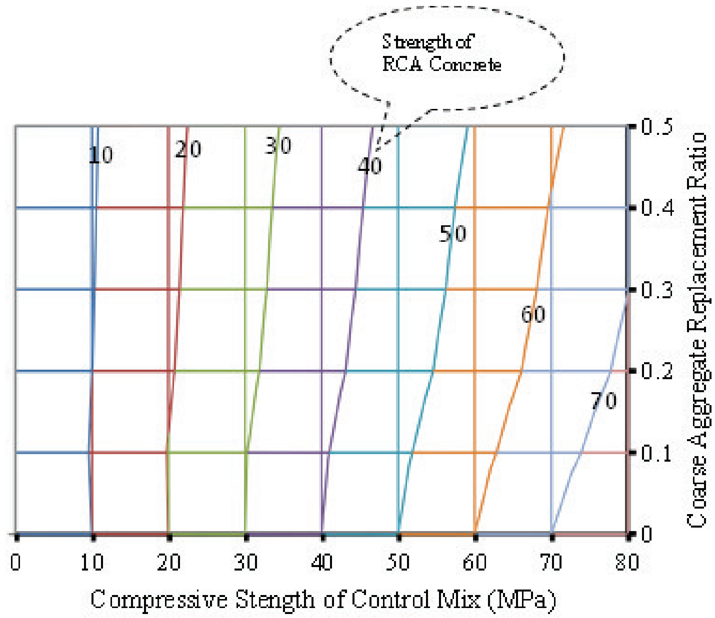


Fig. 13 Nomogram for the selection of strength grade of control mix

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.