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China clay industrial waste in concrete

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Preliminary report

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China clay industrial waste in concrete

This paper deals with the performance of China Clay industrial Waste (CCW) as partial replacement of fine aggregate in concrete. The performance of CCW used in concrete has been ascertained by comparing its compressive strength, split tensile strength, flexural strength, acid resistance & heat resistance with conventional concrete. Test results show that natural sand can be effectively replaced with up to 30% of CCW in concrete without changing its durability.

Key words:
china clay waste, acid resistance, heat resistance, bending stress

Prethodno priopćenje

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Industrijska otpadna kineska glina u betonu

U ovom radu je prikazano istraživanje svojstava industrijske otpadne kineske gline (CCW) kao djelomične zamjene za sitni agregat u betonu. Učinkovitost zamjene sitnog agregata u betonu s otpadnom kineskom glinom određena je uspoređivanjem tlačne, vlačne i savojne čvrstoće, otpornosti na djelovanje kiseline i visokih temperatura betona s CCW-om i s konvencionalnim betonom. Rezultati istraživanja ukazuju da se CCW može koristiti kao djelomična zamjena sitnog agregata u betonu do približno 30 % bez ikakvih promjena u trajnosti betona.

Ključne riječi:
otpadna kineska glina, otpornost na kiselinu, otpornost na visoke temperature, naprezanje pri savijanju

Vorherige Mitteilung

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Industrieller Porzellanerdeabfall im Beton

In der Arbeit wird die Untersuchung der Eigenschaften von industriellem Porzellanerdeabfall (CCW) untersucht, durch welchen im Beton der feine Zuschlagstoff ersetzt wurde. Die Effizienz des Ersatzes des feinen Zuschlagstoffs im Beton durch Abfallporzellanerde wurde durch einen Vergleich der Druck-, Zug- und Beigefestigkeit sowie der Säure- und Hitzebeständigkeit des CCW-Betons und des herkömmlichen Betons ermittelt. Die Untersuchungsergebnisse weisen darauf hin, dass CCW als Ersatz für feinen Zuschlagstoff im Beton teilweise bis zu 30% verwendet werden kann, ohne die Beständigkeit von Beton zu verändern.

Schlüsselwörter:
Porzellanerdeabfall, Säurebeständigkeit, Hitzebeständigkeit, Biegespannung

1. Introduction

Many countries including India suffer from scarce availability of natural concrete ingredients. On the other hand, generation of waste substances as by-products from industries and other sources is increasing on a daily basis. Proper recycling of waste materials is essential for ensuring environmental sustainability. In the late twentieth century, many studies were made on the inclusion of waste materials in concrete as ingredients, which has resulted in improved solutions for dealing with environmental issues such as natural source depletion, waste management, etc. Various waste materials, both natural and artificial, have been tested to determine feasibility of their use in concrete. Even though large quantities of various types of waste are currently available, only some of such waste materials can be effectively used in concrete without affecting the nature of concrete. To enable use of waste materials as ingredients in concrete, their properties should resemble the properties of natural concrete ingredients. Waste materials such as fly ash, copper slag, quarry dust, tyre rubber, granite saw dust, steel slag, crushed clay brick powder, China Clay industrial Waste (CCW), etc. resemble the ingredients of concrete, as has been depicted in previous studies [1-19].

The strength of concrete containing 20 % of Saw Dust Ash (SDA) was determined after 50 days of curing time [1]. The use of 25 % of crushed clay brick powder (CBP) in concrete resulted in a lower unit weight, higher thermal resistance and better absorption rate compared to normal concrete [2]. Similarly, the inorganic sludge (IS) produced by paper industry may be used in place of fine aggregate (50 %) or cement (20 %) [3]. The experimental study of strength characteristics of concrete based on the use of crushed stone dust as fine aggregate reveals that there are increments in compressive strength, flexural strength, and tensile strength of concrete [4]. Favourable results were obtained from the study on the compressive strength of concrete containing lateritic sand (25 %) and quarry dust (75 %) as fine aggregate with a water cement ratio of 0.5 [5]. The increment in compressive, flexural and tensile strength was observed when the crushed stone dust was added as complete replacement for fine aggregate. An experimental study was made for replacing fine aggregate in concrete with five different proportions of granite fines. The results showed that replacement of fine aggregate is effective by incorporating 35 % of granite fines [6]. It was also revealed that the replacement of very fine sand (passing 0.25 mm sieve) by waste marble dust improves mechanical and physical properties and unit weight of concrete [7]. The offshore sand obtained soon after dredging is suitable for concreting within appropriate limits. In addition, offshore sand with low chloride content (below 0.01) may be used in place of fine aggregate [8]. Experimental results revealed that 6 % of tyre rubber may be used in place of sand without affecting mechanical properties of concrete [9]. 10 % of granulated rubber in concrete improves hydro-abrasive resistance [10]. The permeability resistance is high for concrete containing 20 kg/m^3 of rubber powder [11]. The workability increases when 5 % of tyre rubber powder is added [12]. The mixture of tyre granules, steel fibre and polymer fibre in concrete improves resistance to freezing and thawing, increases sound absorption and reduces propagation of cracks [13]. Replacement of fine aggregate by waste glass is considered optimum when up to 20 % of waste glass is added. But this inclusion of waste glass as aggregate tends to decrease workability of concrete considerably [14]. Steel slag (0.7 %) with cement (0.2 %) can be used in stabilization mixes for construction of base courses of pavement structures [15]. The inclusion of steel slag results in improvement of mechanical properties [16]. An increase in the steel slag aggregate ageing period causes decrease in workability and abrasion loss of concrete [17]. Thermoplastic materials can feasibly be used as replacement for natural sand in the quantities of up to 5 %, which reduces the mass of concrete but maintains the compressive strength at levels similar to those for normal concrete [18]. An increase in strength parameters was observed when fine aggregates were replaced with copper slag [19]. The china clay waste ranks among the largely produced waste materials that can be used as fine aggregate in concrete production.

China clay is one of the purest clays with the silica content of about 55-58 %. It is a hydrated Aluminium Silicate Al_2O_3 $2SiO_2$ $2H_2O$ formed by alteration of granite due to hydrothermal metamorphism. 2522181 tonnes of china clay were produced in India in 2010 - 2011. Out of this quantity, 27 % was mined in the state of Kerala in India. China clay is used in the production of many valuable products, and is applied after undergoing one of the two direct processes, washing and pulverizing. These processes have generated nearly 68000 tonnes of waste. This waste is free from clay and contains 86.1 % of silica. Naturally, being a china clay by-product, this waste (CCW) can withstand high temperatures (up to 1300 °C) and it does not swell in water. It is also resistant to chemicals and presents favourable electrical properties [20]. Figures 1.a and 1.b show the unwanted stacking of CCW along roads and at pond embankments, which calls for effective disposal measures.

Figure 1. Unwanted stacking of CCW at: a) pond embankment; b) roadside

The durability of concrete structures is not greatly affected in normal exposure situations. However, in case of aggressive

exposure, concrete structures suffer deterioration due to elevated temperatures, chemical attack, acid attack, etc. Dense impermeable concrete resists acid attack and improves chemical resistance of concrete. Also, the degradation of strength and mass depends upon concrete ingredients, curing period, type of acid, and immersion time [21]. An increase in the concentration of acids results in an increased damage to concrete. At lower acid concentrations, the effect of hydrochloric acid and nitric acid in concrete exceeds that of sulphuric acid. At higher acid concentrations the deterioration of concrete does not depend on the type of acid or on the type of cement [22]. Various experimental studies were made to assess the effect of elevated temperatures on concrete. The rise in temperature initially leads (until 200 °C) to an increase in compressive strength, which is due to rapid dehydration of pore water [23]. When exposed to elevated temperatures, new concrete types such as the self-consolidated concrete and fly ash concrete suffer changes in mechanical and deformation properties that do not correspond to similar changes in normal concrete [24]. The variation of temperature from -20°C to 60°C was found to have effect on mechanical and elastic properties of concrete. The compressive strength, split tensile strength, and modulus of elasticity, have a negative correlation with temperature [25]. Temperature variations have both positive and negative impacts on various properties of concrete. The increment in temperature leads to an increment in initial strength but it fails in increasing and maintaining the long term strength [26].
The China Clay Waste (CCW) can be used for complete replacement of fine aggregate (stone dust) in Semi-Dense Bituminous Concrete (SDBC). It was established that the CCW mix has better Marshall Properties than the stone dust mix [27]. During preliminary research, various proportions of the china clay industrial waste were added to concrete, and the testing of compressive, split tensile and flexural strength was conducted. It was revealed during this testing that 30 % of river sand may be replaced with CCW [28]. In the scope of an extensive study, the flexural behaviour of beams, i.e. of "L" and "T" sections, was tested and it was established that their behaviour was structurally sound and efficient after 30 % of CCW was added [29]. The study undertaken in the scope of this paper was made to address the need for analysing the performance of concrete with CCW under varying loading conditions and environmental exposures.

2. Objectives of the experiment

The ultimate aim of this research is to assess the feasibility of incorporation of China Clay industrial waste (CCW) in concrete, for an optimum 30 % replacement of fine aggregates (FA), using appropriate experiments and modelling. The following objectives have been set in this respect:
- Assessment of weight loss and strength effects caused by elevation of temperature to 100°C, 200°C, 300°C, 400°C, 500°C, and 600 °C.
- Determination of weight loss and strength degradation due to immersion in diluted HCl acid for 7, 30 and 70 days.
- Observation of deflection, and determination of stiffness of beam elements.
- Determination of direct stress, bending stress, and the maximum and minimum stress of beam elements through experiments.
- Determination of deformation and stress in beam elements by modelling using ANSYS software.
- Comparison of the stress and deformation of beam elements obtained from experiments and modelling using ANSYS software.

3. Details of the experiment

3.1 Materials

Virgin materials were chosen as raw materials for concreting. The following materials were used in the experiments: 43 grade OPC cement, crushed rock (20 mm in maximum grain size) as coarse aggregate (CA), and potable water. Locally available river sand was used as fine aggregate, as well as the CCW as its partial replacement. The ingredients were tested as per Indian standard codes. The cement, aggregate, and reinforcement steel were tested based on IS codes 8112-1989 [30], 383-1970 [31] and 1786-1985 [32], respectively. The properties of cement are given in Table 1. The properties of CCW were tested in the laboratory of china clay Industry – M/S, Aathavan, as shown in Tables 2 and 3.

Table 1. Properties of cement

Properties of cement	Value
Specific gravity (no unit)	3.15
Fineness [m^2/kg]	227.80
Initial setting time [min]	45
Final setting time [min]	585
Standard consistency [%]	30

Table 2. Properties of aggregates

Properties of aggregates	FA	CCW	CA
Specific gravity (no unit)	2.80	2.70	2.80
Fineness modulus (no unit)	3.10	2.70	7.50
Water absorption [%]	0.50	0.50	0.50
Surface texture	smooth	smooth	
p^H (no unit)		7.20	
Impact value (no unit)			15.20
Particle shape			angular
Crushing value (no unit)			18.60

FA - fine aggregate, CCW - China clay industrial waste, CA - coarse aggregate

Table 3. Mineral constituents of CCW

Constituents of CCW	Value [%]
SiO_2	86.100
TiO_2	0.110
Al_2O_3	7.910
Fe_2O_3	2.010
MgO	0.010
K_2O	2.710
Na_2O	0.200
MnO	0.030
ClO_3	0.001
SO_3	0.004
H_2O and impurities	0.915

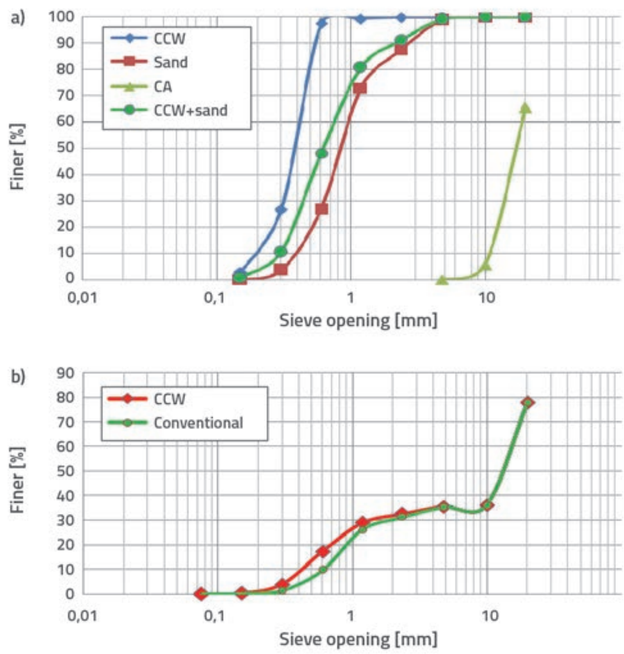

Figure 2. a) Particle size distributions; b) Final composition curve for all aggregates

3.2. Casting and testing of specimens

Based on ingredient testing results, the M30 grade concrete mix was designed as per IS code 10262-2009 [33]. The design mix is defined as follows:

Cement : FA + CCW : CA : water
1 : 1.545 : 2.772 : 0.44

Figure 3. Specimen casting in progress

For preliminary experiments, 54 cubes (150 x150 x 150 mm), 54 cylinders (150 mm in diameter and 300 mm in length) and 54 prisms (100 x 100 x 500 mm) were cast by replacing FA with CCW at the casting yard (Figure 3), using the following replacement proportions: 0 %, 10 %, 20 %, 30 %, 40 % and 50 %. The specimens were tested after 7, 14, and 28 days of water curing. The testing of specimens was conducted in accordance with IS 516-1959 [34] and IS 5816-1999 [35]. The testing of prisms using the Universal Testing Machine (UTM) is shown in Figure 4. The specimen strength values were obtained by inserting test readings in equations (1) to (3). The corresponding results are given in Table 4. When compared, concrete specimens with 30 % CCW (CCCW) exhibited greater strength. The compressive strength, split tensile strength, and flexural strength results are presented in Figures 5, 6, and 7, respectively, to compare conventional and CCCW specimens.

Table 4. Experimental test results for cubes, cylinders and prisms at 28 days

Mix designation	Fine aggregate		Compressive strength [N/mm²]	Split tensile strength [N/mm²]	Flexural strength [N/mm²]
	Sand [%]	CCW [%]			
M0	100	0	31.50	3.35	5.32
M1	90	10	34.00	3.42	5.46
M2	80	20	36.00	3.63	5.66
M3	70	30	37.50	3.85	5.74
M4	60	40	33.00	3.45	5.28
M5	50	50	31.00	3.15	4.88

Figure 4. Flexural strength test on prismsSlika 6. Vlačna čvrstoća cijepanjem uzoraka valjka

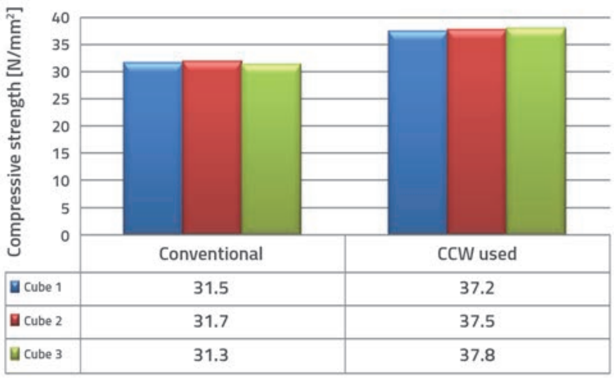

Figure 5. Compressive strength of cubes

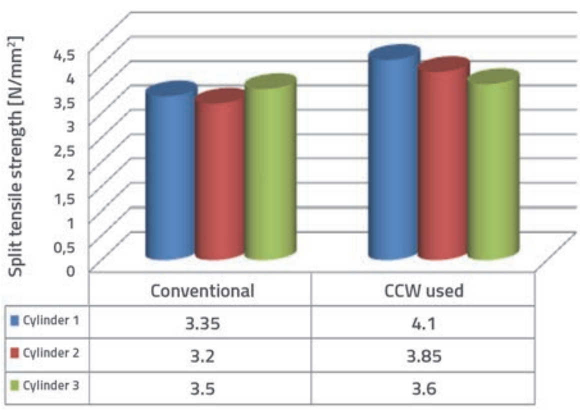

Figure 6. Split tensile strength of cylinders

$$\sigma = \frac{P}{A} \quad (1)$$

$$f_{ct} = \frac{2P}{\pi LD} \quad (2)$$

$$f_b = \frac{Pl}{bd^2} \quad (3)$$

where:

σ - compressive strength of cubes

f_c - split tensile strength of cylinders

f_b - flexural strength of prisms

P - applied load [N]

A - cross sectional area of the cube [mm²]

L - length of cylinder [mm]

D - diameter of cylinder [mm]

l - length of span on which the specimen was supported

b - breadth of prism [mm]

d - depth of prism [mm].

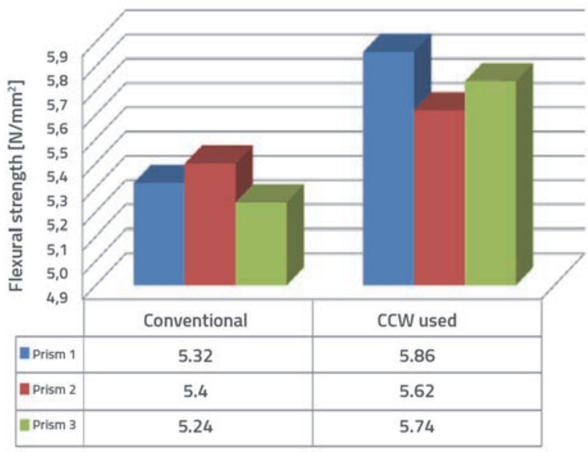

Figure 7. Flexural strength of prisms

3.3. Acid resistance test

The acid resistance test was conducted on cube specimens in order to determine the effect of acid on concrete. In this testing, cube specimens were treated with diluted HCl acid by immersion method. Initially, cube specimens (conventional and CCW used) were cast and cured in water for 28 days. After curing, the specimens were allowed to dry at room temperature for 24 hours. The specimens were then

Table 5. Acid resistance test results

Designation of specimens	Average							
	Weight loss [g]				Compressive strength [N/mm²]			
	Initial	7 days	30 days	70 days	Initial	7 days	30 days	70 days
Conventional	0	18	24	46	31.50	31.40	31.22	31.08
CCW used	0	16	20	42	37.50	35.55	35.40	35.17

immersed in 2 % diluted HCl solution (Figure 8). Two sets (three cubes each) of conventional and CCCW cubes were tested after 7, 30, and 70 days of immersion in acid, based on standard procedure.

Figure 8. Acid resistance test on cubes

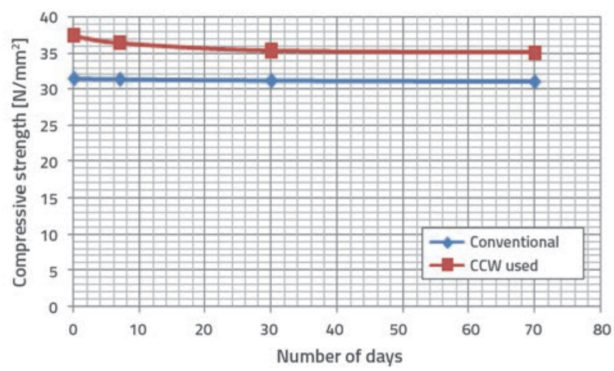

Figure 9. Compressive strength of specimens after immersion in acid

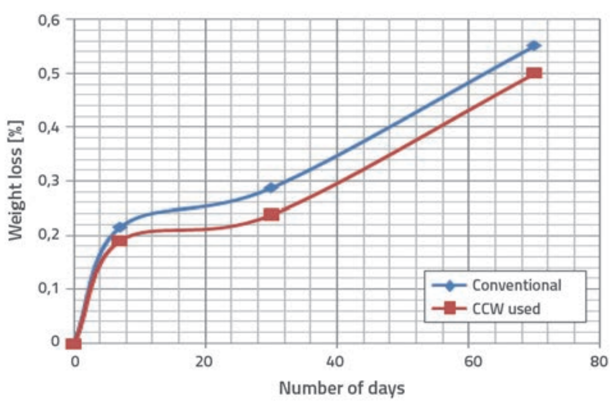

Figure 10. Weight loss in specimens after immersion in acid

Compressive strength values were obtained by substituting the values of applied load and cross sectional area in Eq. (1),. The compressive strength and weight loss were tabulated in Table 5 and plotted as graphs (Figure 9 and 10) to compare the performances. The mean compressive strength of conventional and CCCW cube specimens (size: 150 mm x 150 mm x 150 mm) at normal exposures were 31.50 and 37.5 N/mm^2, respectively. The initial mean weight of conventional and CCCW cube specimens after 28 days of curing amounted to 8340 g and 8385 g, respectively.

3.4 Heat resistance test

After 28 days of curing, 54 conventional and 54 CCCW specimens were subjected to heat resistance testing. The cube specimens were kept in hot air oven (Figure 11) for 1, 2 and 3 hours at constant elevated temperatures [36] of 100°C, 200°C, 300°C, 400°C, 500°C, and 600 °C. The specimens taken out of the oven were kept at ambient air temperature for 12 hours and the weight and compressive strength values were determined, as shown in Figure 12.

Figure 11. Specimens in hot air oven

Figure 12. Compressive strength test on oven dried cubes

Table 6. Heat resistance test results

Duration / Temp. [°C]	Conventional specimens						CCW specimens					
	Mean weight loss [g]			Mean compressive strength [N/mm²]			Mean weight loss [g]			Mean compressive strength [N/mm²]		
	1h	2h	3h	1h	2h	3h	1h	2h	3h	1h	2h	3h
27	0.00	0.00	0.00	31.50	31.50	31.50	0.00	0.00	0.00	37.50	37.50	37.50
100	5.00	15.00	22.00	29.91	29.60	29.29	4.00	11.00	18.00	37.16	36.93	36.76
200	7.00	22.00	31.00	31.49	31.33	31.18	6.50	23.00	30.00	37.49	37.29	37.11
300	12.00	26.00	34.00	32.44	32.27	32.09	11.50	24.00	36.00	38.62	38.40	38.18
400	21.00	32.00	41.00	26.00	25.87	25.56	23.00	30.00	44.00	30.76	30.58	30.40
500	30.00	44.00	52.00	18.89	18.67	17.16	28.00	36.00	47.00	22.49	22.31	22.09
600	48.00	49.00	49.00	17.11	13.16	12.62	42.00	47.00	48.00	15.73	15.51	15.02

The mean values of differences in weight and compressive strength are presented in Table 6 and plotted in graphs as Figure 13 and 14 for both conventional and CCCW specimens.

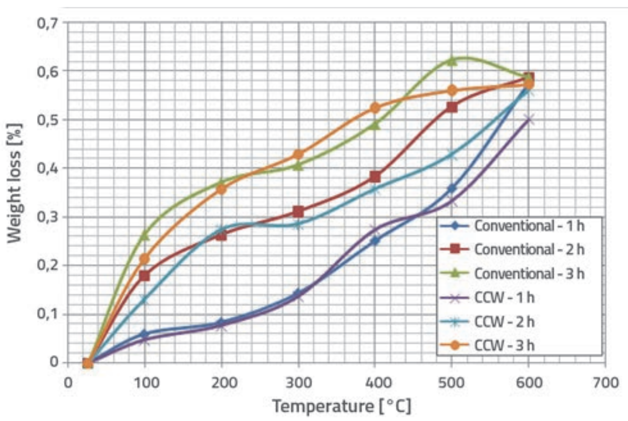

Figure 13. Specimen weight loss after hot air oven drying

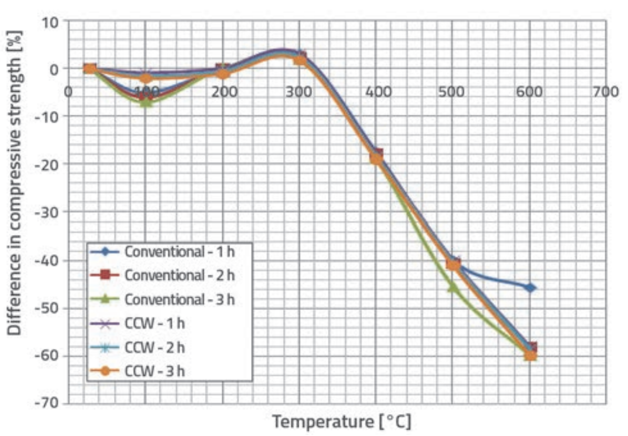

Figure 14. Compressive strength after hot air oven drying

3.5. Testing of beam elements

An optimum replacement of fine aggregate by 30 % CCW was implemented for the casting of beam elements. Six beam element samples were prepared, three with conventional concrete and three with 30 % of CCW. Dimensions and reinforcement details of beams are shown in Figure 15. The elements were detached from the mould after 24 hours and kept for curing in water. After 28 days of curing, the elements were subjected to testing in the loading frame according to recommendations given in IS 516-1959.

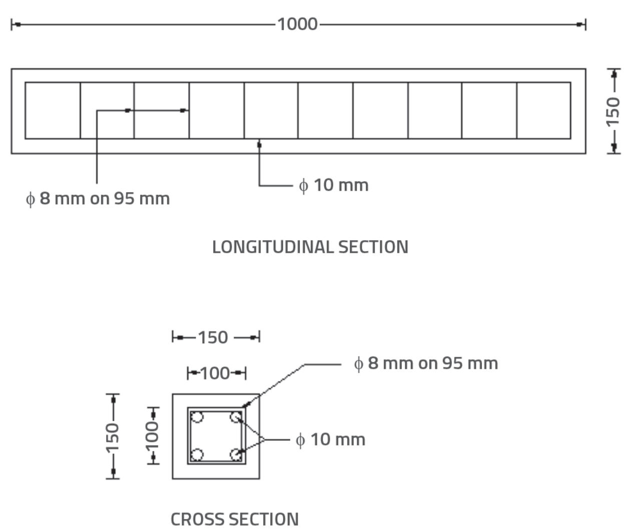

Figure 15. Details of beam elements, dimensions in mm

Before the elements were placed in position, they were marked with grid lines on the surface to observe the crack pattern under loading. Once elements were positioned in the loading frame, strain gauges were attached at a distance of L/3 from ends and mid-span as shown in Figure 16.

Figure 16. Loading of elements

LVDT and dial gauges were positioned under the elements to enable deflection measurements. Once the beam element was placed in position, single point loading was applied on the element using a loading frame 2000 kN in capacity at constant loading intervals over the mid span. Moreover, the crack pattern and the data from LVDT, dial gauge and strain gauge were noted for every load interval. By substituting the observed mean values in Eq. (4) to (8), the elastic properties were calculated as shown in Tables 7. and 8. A stress-strain curve was also generated from this experiment to compare elastic performance, as shown in Figure 17.

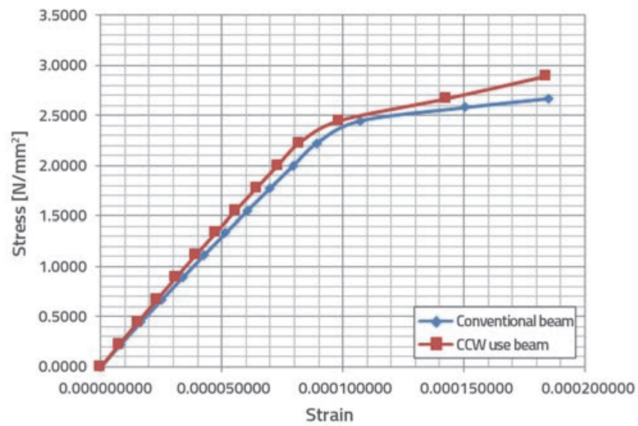

Figure 17. Stress vs. strain curve for beams

$$\sigma_{dir} = \frac{P}{A} \tag{4}$$

$$\sigma_b = \frac{MY}{I} \tag{5}$$

$$\sigma_{max} = \frac{P}{A} + \frac{M}{Z} \tag{6}$$

$$\sigma_{min} = \frac{P}{A} - \frac{M}{Z} \tag{7}$$

$$k = \frac{P}{\delta l} \tag{8}$$

where:
σ_{dir} - direct stress
σ_b - bending stress
σ_{max} - maximum stress
σ_{min} - minimum stress
k - stiffness

Table 7. Elastic properties of conventional beam elements

Load [kN]	Direct stress [N/mm²]	Flexural stress [N/mm²]	Maximum stress [N/mm²]	Minimum stress [N/mm²]	Bending stress [N/mm²]	Stiffness [kN/mm]
0	0.00	0.00	0.00	0.00	0.00	0.00
5	0.23	1.48	4.67	4.22	4.44	2.50
10	0.44	2.96	9.33	8.44	8.89	3.33
15	0.67	4.44	14.00	12.67	13.33	3.75
20	0.89	5.92	18.66	16.89	17.78	3.33
25	1.11	7.41	23.33	21.11	22.22	3.12
30	1.33	8.89	28.00	25.33	26.67	3.00
35	1.56	10.37	32.67	29.56	31.11	2.92
40	1.78	11.85	37.33	33.78	35.56	2.86
45	2.00	13.33	42.00	38.00	40.00	3.00
50	2.22	14.81	46.67	42.22	44.44	3.33
55	2.44	16.30	51.33	46.44	48.89	3.67
58	2.57	17.18	54.13	48.98	51.56	3.87
60	2.67	17.78	56.00	50.67	53.33	4.00

Table 8. Elastic properties of CCCW beam elements

Load [kN]	Direct stress [N/mm²]	Flexural stress [N/mm²]	Maximum stress [N/mm²]	Minimum stress [N/mm²]	Bending stress [N/mm²]	Stiffness [kN/mm]
0	0.00	0.00	0.00	0.00	0.00	0.00
5	0.22	1.48	4.67	4.22	4.44	2.50
10	0.44	2.96	9.33	8.44	8.89	3.33
15	0.67	4.44	14.00	12.67	13.33	3.75
20	0.89	5.92	18.67	16.89	17.78	3.33
25	1.11	7.41	23.33	21.11	22.22	3.12
30	1.33	8.89	28.00	25.33	26.67	3.00
35	1.56	10.37	32.67	29.56	31.11	2.92
40	1.78	11.85	37.33	33.78	35.56	2.86
45	2.00	13.33	42.00	38.00	40.00	3.00
50	2.22	14.81	46.67	42.22	44.44	3.33
55	2.44	16.30	51.33	46.44	48.89	3.67
60	2.67	17.78	56.00	50.67	53.33	4.00
65	2.89	19.26	60.67	54.89	57.78	4.33

P - ultimate load [N]
A - cross sectional area of element [mm²]
M - bending moment [Nmm]
Y - 0.5 d [mm]
l - deflection [mm]
I - moment of Inertia [mm⁴
Z - sectional modulus [mm³].

3.6. Numerical analysis

The deformation and stress can be determined at certain locations on the elements through experimental study. However, simulation helps in determining the stress distribution, deflection etc. over the entire length of the elements. Moreover, simulation helps in the validation of the results obtained through experiments, and ensures the feasibility of using CCW as partial replacement of fine agregates. The data in Table 9 were considered while simulating the beam element by means of ANSYS modelling. Reinforcement details with geometry of beam elements are shown in Figure 15. The deformations, flexural stress and bending stress corresponding to ultimate mid-point loading (with end condition) were studied based on the ANSYS modelling. The deformation and normal stress values for conventional and CCCW beam elements are shown in Figures 18 and 19.

4. Results and discussion

The performance of the concrete containing CCW as 30 % of fine aggregate is discussed in this section based on test results for specimens and beam elements. Moreover, mechanical parameters are clearly compared with those of conventional concrete.

4.1. Compressive strength of cubes

Figure 5 shows that the mean compressive strength values of conventional and CCCW cubes amount to 31.70 N/mm² and 37.50 N/mm² respectively. The compressive strength of CCCW cubes exceeds by 18 % that of conventional cubes.

Table 9. Data for simulation

Parameters	Conventional concrete	CCW used
Poisson's ratio	0.280	0.278
Density [kg/m³]	2400	2415
Young's modulus [N/mm³]	27400	29850
Load condition	Single point loading at mid span	Single point loading at mid span

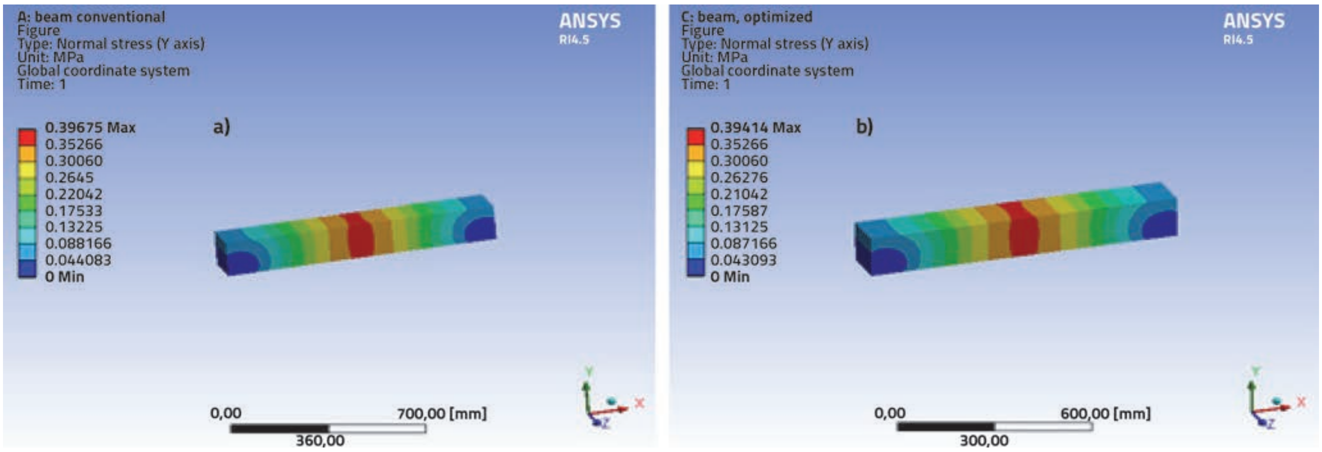

Figure 18. Deformations in beams: a) conventional concrete, b) concrete with CCW

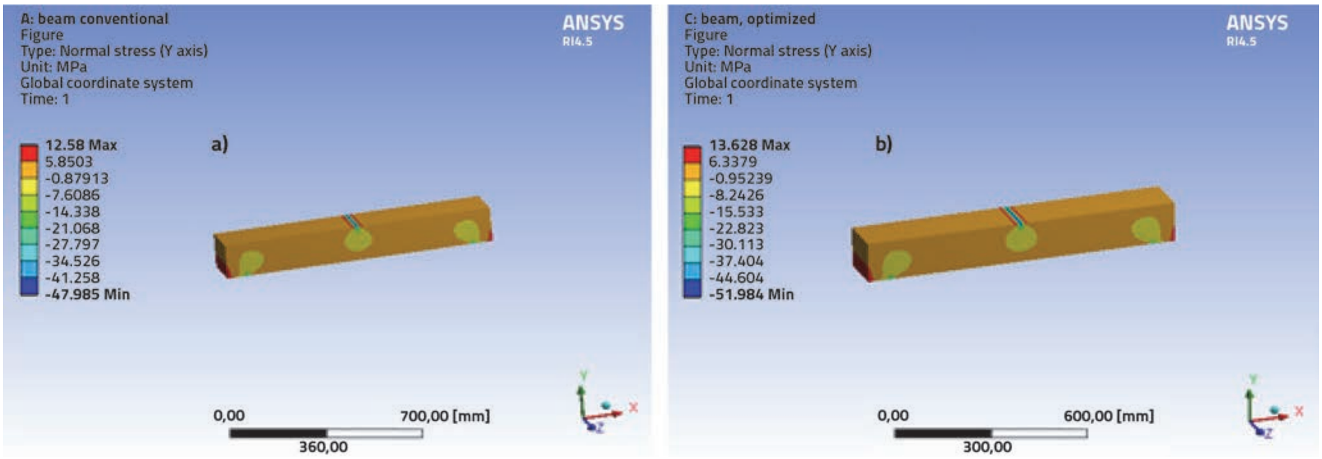

Figure 19. Normal stress in beams: a) conventional concrete, b) concrete with CCW

4.2. Split tensile strength of cylinders

Figure 6 shows that the mean split tensile strength of conventional and CCCW cylinders amounts to 3.35 N/mm^2 and 3.85 N/mm^2 respectively. The split tensile strength of CCCW cylinders exceeds by 15 % that of conventional cylinders.

4.3. Flexural strength of prisms

Figure 7 shows that the mean flexural strength of conventional and CCCW prisms amounts to 5.32 N/mm^2 and 5.74 N/mm^2, respectively. The flexural strength of CCCW prisms exceeds by 8 % that of conventional prisms.

4.4. Effect of exposure to acid

However, both specimens lose their compressive strength and weight with the time of contact with acid. According to Table 5, the mean weight loss of CCW-containing concrete specimens is by 2 g, 4 g and 4 g lower compared to conventional specimens for 7 days, 30 days and 70 days, respectively. Similarly, the maximum average compressive strength attained by CCCW specimens exceeds by 4.15 N/mm^2, 4.18 N/mm^2 and 4.09 N/mm^2 that of conventional concrete specimens for 7 days, 30 days and 70 days, respectively.

Figures 9 and 10 show the drop over time in the % of mean compressive strength and % of mean weight loss for cube specimens exposed to diluted HCl solution. The effect of diluted HCl solution on conventional specimens is greater compared to CCCW specimens. In other words, specimens containing CCW possess higher resistance to the dilute HCl acid.

At all experimented ages (7 days, 30 days and 70 days), lesser reduction in weight is observed in CCCW specimens compared to conventional ones. This is due to the effective filling of micro pores between aggregates by the smaller sized CCW particles. The Particle size distribution curves for CA, FA and CCW and final composition curves of aggregates for CCCW and conventional concrete are shown in Figures 2.a and 2.b.

The compressive strength of CCW concrete specimens was found to be superior to conventional specimens. Siliceous properties of CCW particles hinder reaction of acid at the concrete surface. Thus a smaller reaction is observed on the surface even after 70 days of immersion. This resulted in higher compressive strength in case of CCW concretes compared to conventional ones.

4.5. Effect of temperature

As can be seen in Table 6, the mean weight loss in conventional concrete specimens at every increment of 100° C in the temperature range from 100° C to 600° C for the duration of 1 hour, 2 hours and 3 hours, amounts to 5 to 48 grams, 15 to 49 grams, and 22 to 49 grams, respectively. Meanwhile, the weight loss in the CCW specimens amounts 4 to 42 grams, 11 to 47 grams, and 18 to 48 grams, respectively. The mean compressive strength in conventional concrete specimens at every increment of 100° C in the temperature range of 100° C to 600° C for the duration of 1 hour, 2 hours and 3 hours, amounts to 29.91 to 17.11 N/mm^2, 29.6 to 13.16 N/mm^2, and 29.29 to 12.62 N/mm^2, respectively; in CCCW specimens the corresponding values amount to 37.16 to 15.73 N/mm^2; 36.93 to 15.51 N/mm^2, and 36.76 to 15.02 N/mm^2, respectively. It is therefore obvious that a bigger loss of strength in the percentage of initial strength occurs in CCCW compared to conventional concrete.

Figure 13 and 14 display the variation in the % of mean weight loss and % of mean value of differences in compressive strength of the cubes, as caused by the intensity of temperature and duration of exposure. In the temperature range of 200 to 300^{0}C, the compressive strength of both conventional and CCCW cube specimens increased slightly. This is obvious from the little peak on the graph shown in Figure 14. Both conventional and CCW based specimens are affected by temperature. However, the compressive strength of CCCW specimens was found to be higher at each temperature level compared to conventional specimens. This higher compressive strength is due to thermal properties of CCW ingredients. The loss in weight of both conventional and CCCW specimens was found to be similar at some temperature levels. However, the CCCW specimens show a little lesser weight loss at most temperature levels due to their ability to withstand temperatures of up to 1300°C.

The compressive strength of CCCW specimens at various temperatures and time intervals is superior to conventional specimens. The concrete with CCW exhibits better behaviour up to 350°C but, after that point, both concrete types behave the same. In fact, the situation reverses because, when expressed in % of loss of compressive strength, CCCW lost more strength, although its absolute strength is higher compared to conventional concrete. The temperature increment from room temperature to 600˚C shows that conventional concrete lost 45.7 % of its initial strength, whereas CCCW lost 58.1 %. When the temperature is maintained at 600˚C, the % of loss in strength for 1 hour and 3 hours of exposure amounts to 26.25 % and 4.51 % for conventional and CCCW concrete, respectively. This clearly shows that at prolonged exposure, the % of loss in strength is higher in conventional concrete compared to CCCW concrete. This is mainly due to better bonding between CCW and aggregate, but also to higher thermal stability of CCW.

4.6. Performance of beam elements based on experiments

The cracks initially formed at the bottom fibre of the mid-span in both conventional and CCCW beam elements at mid-point loading [37] using structural loading frame (Figure 15). These cracks developed to the top until the beam failed at ultimate load.

The stress and stiffness values calculated for 5 kN load increments on both conventional and CCCW beams are presented in Tables 7 and 8. The ultimate load carrying capacities of both beams amounted to 60 kN and 65 kN, respectively. The direct stresses were 2.67 and 2.89 N/mm^2; the flexural stresses were 17. 78 and 19.26 N/mm^2, the maximum stress - compressive stress values were 56.00 and 60.67 N/mm^2, the minimum stress - tension stresses values were 50.67 and 54.89 N/mm^2, and the bending stresses were 53.33 and 57.78 N/mm^2, respectively. The stiffness values of both beams were 4.00 and 4.33 kN/mm. The strength and stiffness parameters were high because of the micro structure of the CCW material, which helps in effective bonding and filling of voids.

The stress values of the CCCW beam were comparatively high and strain values were low because of the increase in the Young''s modulus caused by its addition (Figure 17).

4.7. Performance of beam elements based on simulation

The deformation and normal stress values were obtained through simulation using the ANSYS modelling software. The maximum deformations in conventional and CCCW beam elements amount to 0.39675 mm and 0.39414 mm for ultimate loads of 60 kN and 65 kN, respectively. Flexural and bending stresses due to ultimate load in CCCW beam element amount to 13.63 N/mm^2 and 51.98 N/mm^2, respectively, as shown in Figure 19. Flexural and bending stresses due to given ultimate load in conventional element are 12.58N/mm^2 and 47.98 N/mm^2, respectively, as presented in Figure 20. As can be seen in Table 5, flexural and bending stresses due to ultimate load in the CCCW beam element amount to 19.25N/mm^2 and 57.77 N/mm^2, and to 17.77 N/mm^2 and 53.33 N/mm^2 in conventional elements. The ultimate loads of conventional and CCCW elements obtained during experiments amounted to 60 kN and 65 kN, respectively. The same maximum strengths of the beams were observed through simulation. Moreover, the stresses observed from the experiments and simulations are similar in nature. Thus this resemblance between the experimental and analytical results shows that the concrete behaviour actually improves after the CCW is added.

The results obtained by ANSYS modelling and experiments show that CCCW elements are capable of withstanding higher flexural and bending stress compared to conventional elements.

5. Conclusion

The following conclusions can be made based on the experimental investigations and analysis using ANSYS modelling:

- The incorporation of CCW in concrete as fine aggregate helps in increasing the compressive strength, flexural strength, and split tensile strength of concrete significantly. These positive effects are mainly due to the properties of the CCW particles that disperse in the matrix of cement paste phase of concrete, and to adequate interlocking with concrete aggregate. The addition of CCW results in the formation of interfacial region between the particles of aggregates and hardened cement paste phase, which exerts a great influence on the performance of concrete.
- The heat resistance of concrete increases with an increase in the percentage of CCW. A superior thermal stability of CCW particles helps in retaining compressive strength of concrete cubes.
- The exposure to dilute acids tends to reduce the compressive strength of concrete. However, this reduction in strength depends on the duration of immersion, type and concentration of acid, and mineral aggregate properties. Since CCW particles do not exhibit considerable change of properties when reacting with acids, the concrete containing CCW will also possess greater resistance to acids compared to conventional concrete.
- The experiments on beam elements help in assessing elastic performance of concrete under midpoint loading. It is obvious that elastic performance of concrete increases with the addition of CCW.
- The numerical simulation using the ANSYS software points to an increase in elastic performance of beam elements containing CCW.
- The experimental research results show that CCW can be used as partial replacement of fine aggregate in concrete in the proportion of about 30 %, without any effect on the durability of concrete. So, this contributes to the cost effectiveness of concreting, environmental sustainability, and reclamation of waste landfills.

A future study on the performance of CCW for joints of structural elements can be made to examine its behaviour with and without addition of admixtures under normal and seismic loading conditions.

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