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Sustainable deployment of crushed concrete aggregates strengthened with cement and sand

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ABSTRACT

Purpose: Paper assessed the feasibility of crushed concrete aggregates (CCA), a subsidiary of construction and demolition (C&D) waste, blended with cement and sand to form a composite for civil engineering field applications.

Design/methodology/approach: The compaction and strength characteristics of CCA were observed by conducting Proctor compaction and California Bearing Ratio (CBR) tests. Different proportions of CCA, sand and cement were used. Moreover, the effect of curing period (0, 4, 7, 14 and 28 days) was also studied. In addition, regression analyses were performed to develop empirical expressions to predict the compaction and strength characteristics of the CCA composite.

Findings: Increasing the CCA content up to 50% increases the maximum dry unit weight (MDUW) and decreases the optimum moisture content (OMC). However, on further increasing its content the MDUW decreases and OMC increases. Percent increase in the CBR value can go up to 412% if the CCA content is increased up to 50%. However, the percent reduction in CBR of about 20% can take place if 100% CCA content is used. Moreover, multiple regression shows that the experimental results are in good agreement with the predicted values.

Research limitations/implications: The results obtained are purely dependent on the type of material. However, they are in favour of the used material as a probable option for road sub-base layer, and also for reducing burden on available natural resources. Therefore, it is recommended to conduct some initial tests to confirm the feasibility of the material.

Practical implications: The proposed study will guide the design Engineers to choose CCA as one of the potential materials for road construction.

Originality/value: It was observed that there is a need to maximize the utilization of C&D waste without making any compromise with its mechanical properties. So keeping that in view, the present study was conducted.

Keywords: Sustainability, Crushed concrete aggregate, Cement, Sand, Compaction, CBR, Multiple regression

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METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

In developing countries, the increasing population, urbanization, and industrialization are inflicting a challenge on sound waste management practices [1]. Moreover, the increasing demand for material resources for the construction of civil engineering projects started posing a threat to the available natural resources [2]. The newly constructed structures are replacing the old structures thereby producing large quantities of waste, which are either disposed of to open areas or diverted to the landfills. In India, as of 2017, 9.3 million metric tonnes of recyclables (glass, plastic, metals and papers) and 16.5 million metric tonnes of inert waste gets generated [2]. Researchers around the globe are investigating important factors, like, waste generation, composition, quantification, management, recycling, greenhouse gas (GHG) emissions, and life cycle assessment [1, 3-8].

Construction and demolition (C&D) waste comprises concrete waste, brick or concrete powder material, and so forth [9-11]. Researchers are working on different ways to utilize C&D waste in the construction industry. Kou and Poon [12] studied the fresh and hardened properties of self-compacting concrete (SCC) made with recycled concrete aggregates (RCA) as both fine and coarse aggregates. It was recommended that the fine and coarse RCA can be used in SCC production. Kapoor et al. [13] reported the results of an experimental investigation conducted to study the durability properties of SCC made with RCA as partial or full replacement of natural aggregates (NA). The results indicated with the addition of supplementary cementitious materials (SCMs), 10%, in RCA (50%) compensated for the loss of durability properties. However, replacing NA with 10% RCA was not found to be effective in fully compensating the loss of durability properties. Kapoor et al. [14] studied the water permeation properties of SCC containing fine and coarse RCA as a replacement of fine and coarse NA. It was observed that the water permeation depth increases with increasing coarse RCA but has marginal effect, if fine RCA is used. Arora and Singh [15] reported the results of an experimental investigation to calculate the flexural fatigue performance of concrete made with RCA. It was observed that concrete containing 100% RCA and 10% silica fumes (SF) performed better than concrete containing 100% NA. Arora et al. [16] studied the strength performance of RCA containing SCMs and observed that concrete made with RCA containing SCMs enhanced its mechanical properties. Sharma [17] evaluated the properties of SCC containing pozzolanas, microfiber, and RCA. It was found that RCA concrete offers less strength than concrete made with NA because the interfacial bond between the RCA and mortar is weak. However, the interfacial bond can be strengthened by adding microfibers and pozzolanas in the concrete. Singh et al. [11] carried out an experimental investigation to study the workability and strength properties of SCC made with RCA using ultrafine recycled powder (RP) and SF. It was observed that the strength of concrete made with RCA offered promising results.

Researchers have been working on finding ways of incorporating C&D waste as an unbound material in road pavement base and sub-base. Park [18] carried out laboratory and field studies and found out that the stability and shear resistance of RCA in dry conditions was higher than gravels and equal to or better than those of crushed stone aggregate. Akbulut and Gurer [19] evaluated the utilization of aggregates produced from marble quarry waste in asphalt pavements. The physical properties were observed to be within specified limits and, therefore, recommended that these can be used as an aggregate in light to the medium trafficked pavements. Chidiroglou et al. [20] investigated the physical properties of C&D waste for re-use as engineering fill. The similarity between Crushed concrete aggregates (CCA) and that obtained directly from the demolition site was observed. Arulrajah et al. [21] characterized the recycled crushed brick (RCB) when blended with RCA and crushed rock (CR) for pavement sub-base applications. It was concluded that up to 25% RCB could be added to RCA and CR blends in pavement sub-base applications. Herrador et al. [22] verified the feasibility of using C&D waste as base pavement layers of road surfaces and advocated its applicability to use as base pavement layers. Arulrajah et al. [23] studied the geotechnical and geo-environmental properties of C&D material (RCA, RCB, CR, reclaimed asphalt pavement (RAP) and fine recycled glass (FRG) for pavement sub-base applications. It was observed that RCA and CR proved to be a superior material to typical quarry granular sub-base materials. Viera and Pereira [24] reviewed some past studies to assess the utilization of C&D waste in Geotechnical applications. As the past studies gave promising results, hence, it was promoted to use C&D waste in geotechnical applications. Arisha et al. [25] evaluated the performance of C&D waste for pavement construction. Blends of RCA with recycled clay masonry (RCM) as unbound granular material were prepared. It was predicted that the pavement made with RCA performed better than virgin material.

It was observed from the literature that C&D waste may perform inferior to virgin material, and to compensate this, cement stabilization is an option. Taha et al. [26] presented the results of an experimental study on cement stabilized RAP and RAP-virgin aggregates mixes. For RAP aggregate to function as a structural component of pavement, it should be stabilized with cement rather than when blended with only virgin aggregate. Behiry [27] carried out an experimental study to assess the feasibility of using RCA blended with limestone aggregate (LSA) for pavement base or sub-base application. Improvement in the performance of the blended mix was observed with the inclusion of RCA. Xuan et al. [28] studied the behaviour of cement-treated reclaimed C&D waste (mixed masonry and concrete waste) as a road base. Results indicated that decreasing masonry content, as well as increasing cement content and degree of compaction, enhanced its mechanical properties. Zhao et al. [29] studied the feasibility of using RCA obtained from a precast block for the production of a new building block. The results indicated that using RCA can marginally reduce the compressive strength and affects the durability of the concrete. However, by using 100% RCA the compressive strength of concrete could reach the prescribed strength after 28 days of curing.

From the literature, it is clear that there is a need to maximize the utilization of C&D waste without making any compromise with its mechanical properties. So, in the present study, a subsidiary of C&D waste, CCA, is blended with OPC to know its compaction and strength characteristics and to assess its feasibility as a probable replacement of natural material for road pavement sub-base layer. Modified Proctor compaction tests were carried out to study the compaction characteristics, and CBR tests to study the strength and load-penetration characteristics. Three different blended composites, CCA-sand (CCA-S), CCA-cement (CCA-C) and CCA-sand-cement (CCA-S-C) were prepared. CBR tests conducted on CCA-S composite alone were subjected to 4 days of curing. However, when cement is added to the composite, the curing period is extended up to 28 days with the variation of 4, 7, 14 and 28 days. Moreover, regression analyses were performed to develop empirical expressions to predict the compaction and strength characteristics of the composite.

2. Materials

The soil used in this study is classified as poorly graded fine sand (SP) as per ASTM standard [30]. The grain-size distribution curve of the sand, before and after compaction, used in this study is shown in Figure 1. Its physical properties are presented in Table 1.

CCA used in the study is shown in Figure 2. It is classified as well-graded gravel (GW) as per ASTM standard [30]. The grain-size distribution curve of CCA, before and after compaction, used in the present study is shown in Figure 1, and its physical properties are presented in Table 1.

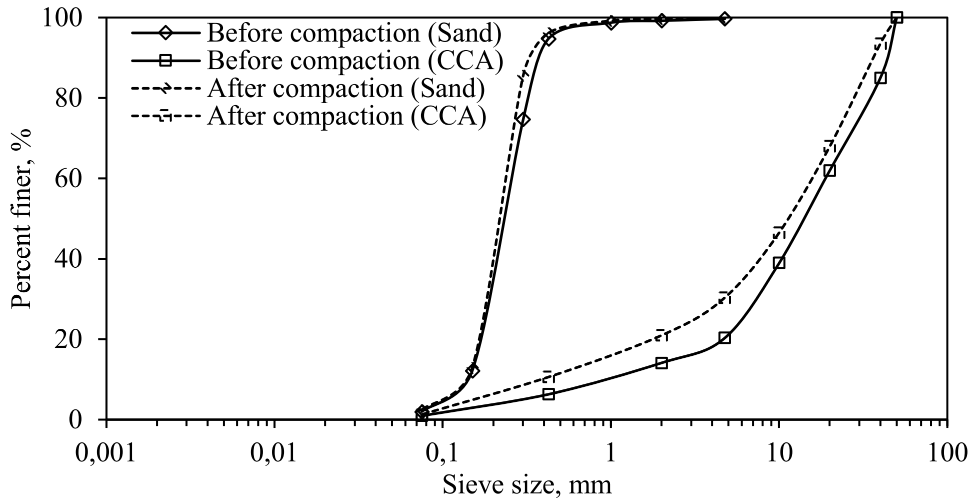

Fig. 1. Grain-size distribution of sand and CCA

Table 1.
Physical properties of sand and CCA

Type	D_{10}, mm	D_{30}, mm	D_{60}, mm	C_u	C_c	$\gamma_{d\text{-}max}$, kN/m^3	$\gamma_{d\text{-}min}$, kN/m^3	G	w, %
Before compaction (Sand)	0.15	0.19	0.25	1.67	0.96	16.70	13.70	2.64	1.01
Before compaction (CCA)	3.00	8.00	18.00	6.00	1.19	17.10	14.60	2.46	2.03

a) b) c)

Fig. 2. CCA used in the study; a) before crushing, b) during crushing, and c) material used in the present study after crushing

OPC (43-grade) used in the present study is procured from the local market. Its physical properties [31] are presented in Table 2.

Table 2.
Physical properties of OPC

Property	Value
Fineness, %	4.00
Standard consistency, %	33.00
Specific gravity	3.15
Initial setting time, minutes	32.00
Final setting time, minutes	590.00
Soundness, mm	3.00
Specific surface, m^2/Kg	289.00

3. Testing program

To evaluate the compaction and strength characteristics of CCA-S, CCA-C and CCA-S-C composites under unsoaked and soaked conditions, an extensive experimental investigation was carried out. Firstly, the physical properties of individual materials, CCA, sand, and OPC, were evaluated using standard procedures. Secondly, the compaction characteristics were determined for different composites. Finally, the strength characteristics of the composite, that is, CCA mixed in different proportions (10, 20, 30, 40, 50 and 100%) by dry weight, with sand and cement (0, 3 and 5%) were evaluated.

3.1. Compaction test

The modified proctor compaction test [32] was adopted to evaluate the compaction characteristic of the CCA-S-C composite. The summary of compaction tests conducted with varying proportions of CCA mixed with sand and cement is presented in Table 3.

Table 3.
Test plan for compaction and CBR tests

Series	I $*						
CCA, %	0	10	20	30	40	50	100
Sand, %	100	90	80	70	60	50	0
Cement, %	0	0	0	0	0	0	0
Series	II #*						
CCA, %	0	10	20	30	40	50	97
Sand, %	97	87	77	67	57	47	0
Cement, %	3	3	3	3	3	3	3
Series	III #*						
CCA, %	0	10	20	30	40	50	95
Sand, %	95	85	75	65	55	45	0
Cement, %	5	5	5	5	5	5	5

*CBR tests were subjected to curing period only.
$ Curing period of 4 days.
# Curing period of 4, 7, 14 and 28 days

3.2. CBR test and its sample preparation

CBR test [33] was adopted for evaluating the strength behaviour of CCA composite. CBR is defined as the ratio of unit load on the piston required to penetrate 2.5 mm and 5 mm of the test material to the unit load required to penetrate a standard material of well-graded crushed stone [33]. Generally, the ratio corresponding to 2.5 mm piston penetration is taken as a CBR value. In case, if the ratio corresponding to 5 mm piston penetration is higher, then, it is recommended to re-run the test called a check test.

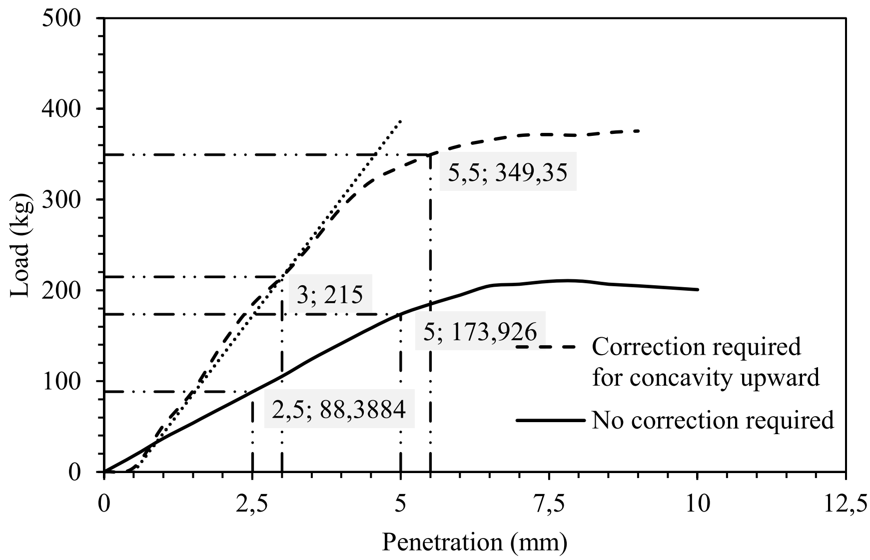

Fig. 3. Methodology adopted for correcting the load-penetration curves

If the check test gives a similar result, then, the CBR value corresponding to the 5 mm piston penetration is considered (Fig. 3). The summary of CBR tests conducted on different composites is presented in Table 3.

For the preparation of the test specimen, primarily, all the ingredients were mixed in a dry state. Secondarily, water content corresponding to the OMC of the respective composite was added. The mixing was continued until the composite achieves a uniform texture. The individual weight (dry) of each of the ingredients in a composite was decided based on the MDUW (maximum dry unit weight) of the respective composite. For instance, if the volume of the CBR mould is "V" and the MDUW of the composite is "$\gamma_{composite}$", then the dry weight of the composite is "$\gamma_{composite}$ x V". After obtaining the dry weight of the composite, the individual weight (dry) of each of the ingredients of the composite can be obtained by multiplying its content (%) with the dry weight of the composite. For each of the test results reported, an average of 3 specimens was taken to ensure the uniformity of the tests.

4. Results and discussion

An extensive experimental program has been carried out to evaluate the compaction and strength characteristic of CCA composite. For this, the modified proctor compaction and CBR tests were conducted.

4.1. Compaction test

The compaction curves obtained from the compaction tests conducted on all the combinations of CCA, sand, and cement are shown in Figure 4. Figures 4a, 4b and 4c show the compaction curves obtained for 0%, 3% and 5% cement content, respectively.

Effect of CCA content

It can be seen from Figure 5 that as the CCA content is increased from 0 to 50%, the OMC of CCA-S-C composite decreases whether cement is added or not. However, on further increasing the CCA content to 100% the OMC of the CCA-S composite decreases. But, on increasing the CCA content to 97% and 95% the OMC of the CCA-S-C composite remains almost unchanged. For CCA-S composite as the CCA content is increased from 0% to 50%, the OMC decreases from 13% to 10.3%, respectively. On further increasing the CCA content to 100%, the OMC value decreases to 10%. For CCA-S-C composite as the CCA content is increased from 0% to 50%, the OMC decreases from 13.6% to 10.6%, respectively. On further increasing the CCA content to 97%, the OMC value remains unchanged at 10.6%. For CCA-S-C composite as the CCA content is increased from 0% to 50%, the OMC decreases from 14% to 11.2%, respectively. On further increasing the CCA content to 95%, the OMC value is 10.25%. Hence, the variation of CCA has a different effect on CCA-S composite than the CCA-S-C composite. In CCA-S composite the increase in CCA content results in a decrease in the void volume because the larger particles are replacing the smaller ones, which reduces the specific surface. On the other hand, that is, in CCA-S-C composite the unchanged OMC value on increasing the CCA content to 100% is maybe due to the presence of finer cement particles which compensates for the reduction in the void volume, thereby balancing the specific surface.

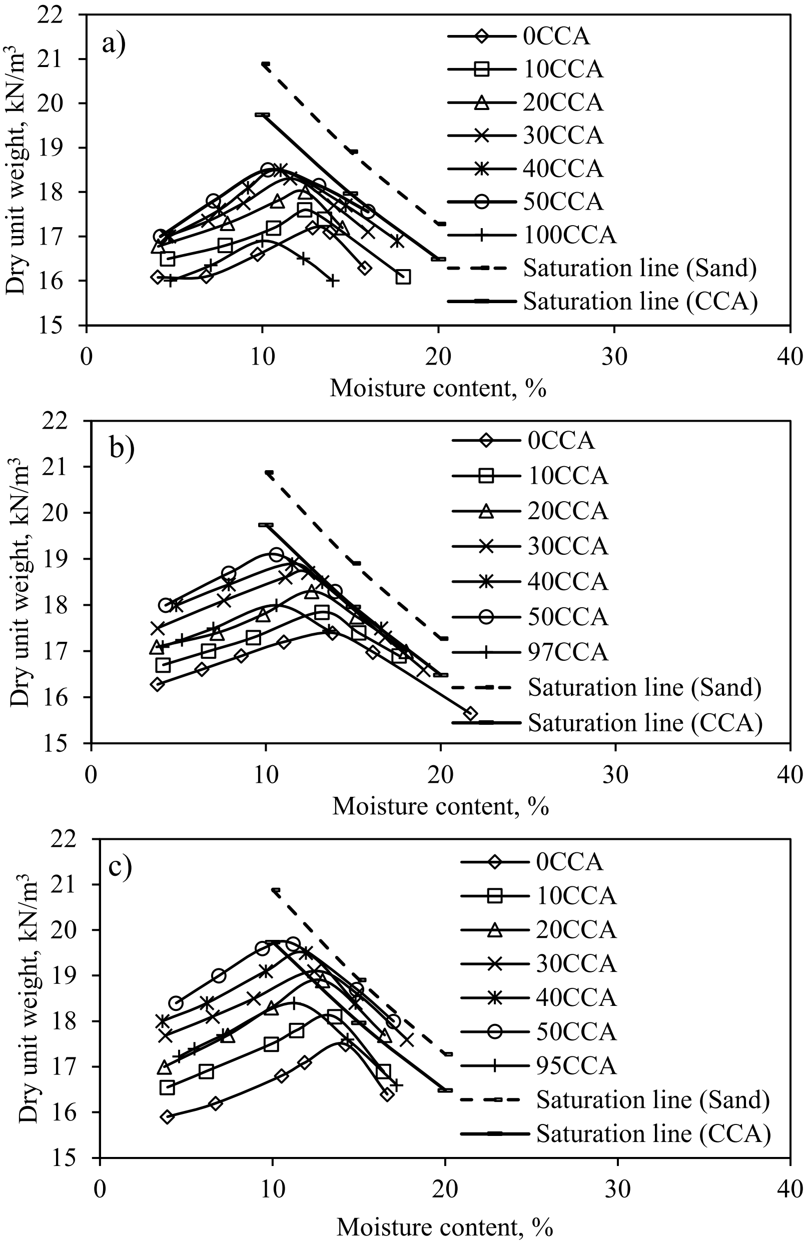

Fig. 4. Compaction curves obtained from all the test combinations for a) without cement, b) with 3% cement content, and c) with 5% cement content

It can be seen from Figure 5 that as the CCA content is increased from 0% to 50%, the MDUW of the composite increases whether cement is added or not. However, on increasing the CCA content to 100% the MDUW of the composite decreases. For CCA-S composite as the CCA content is increased from 0% to 50%, the MDUW increases from 17.2 kN/m^3 to 18.5 kN/m^3, respectively. However, on increasing the CCA content to 100% the MDUW of CCA-S composite decreases to 16.9 kN/m^3. Similarly, for CCA-S-C composite as the CCA content is increased from 0% to 50%, the MDUW of the composite increases from 17.4 kN/m^3 to 19.1 kN/m^3. On further increasing the CCA content to 97%, the MDUW decreases to 18 kN/m^3. For CCA-S-C composite as the CCA content is increased from 0% to 50%, the MDUW of the composite increases from 17.5 kN/m^3 to 19.7 kN/m^3. On further increasing the CCA content to 95%,

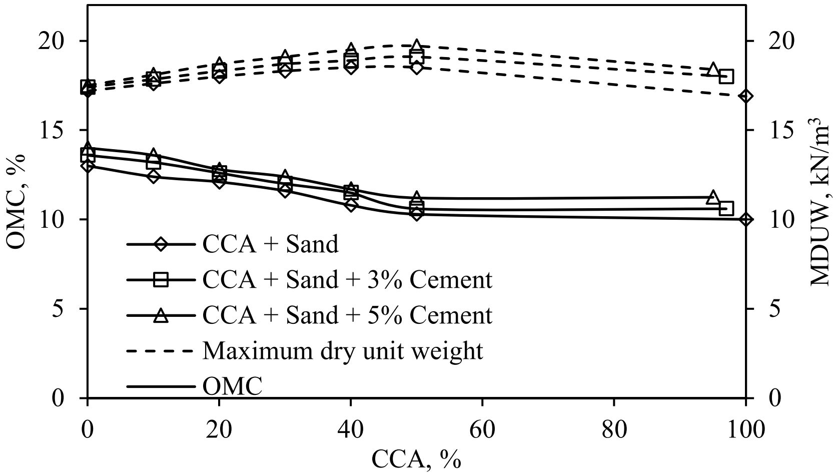

Fig. 5. Effect of CCA content on OMC and MDUW of CCA-S and CCA-S-C composite

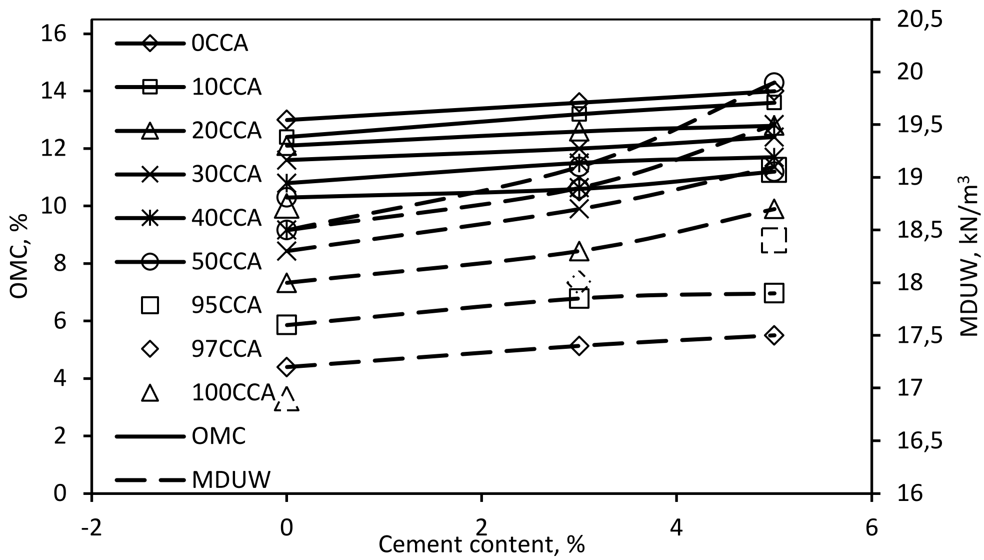

Fig. 6. Effect of cement content on OMC and MDUW

the MDUW decreases to 18.4 kN/m^3. This shows that up to 50% CCA content the density of the composite is improving and on further increasing the CCA content to maximum, the reduction in density is observed. The increase in MDUW of the composite may be attributed to the reduction in void volume until the CCA content is increased by up to 50%. On further increasing the CCA content to the maximum results in a composite of CCA only, or, CCA-C only. Without sand particles in a composite, it will result in a relatively less dense mix. Therefore, after increasing the CCA content beyond 50% and to the maximum, the decrease in MDUW is because of the reduction in the denseness of the mix.

Effect of cement content

It can be seen from Figure 6 that as the cement content is increased there is an increase in the OMC of the CCA-S-C composite. For 0% CAA content, on increasing cement content from 0% to 3% and then to 5% the OMC increases from 13% to 13.6% and then to 14%, respectively. For 10% CAA content, on increasing cement content from 0% to 3% and then to 5% the OMC increases from 12.4% to 13.2% and then to 13.6%, respectively. For 50% CAA content, on increasing cement content from 0% to 3% and then further to 5% the OMC increases from 10.3% to 10.6% and then to 11.2%, respectively. For 100% CCA content (0% cement content), the OMC is 10%. For 97% CCA content (3% cement content), the OMC is 10.6%. For 95% CCA content (5% cement content), the OMC is 11.25%. The increase in OMC value with the increase in cement content is because of the increase in the specific surface of the grains. As the cement particles are very fine as compared to the sand as well as CCA, the specific surface of the composite will be increased with the increase in cement content. More the specific surface of the composite more will be the requirement of water for lubricating the grain's surface of the composite, thereby increasing the OMC value.

Figure 6 also shows the effect of cement content on the MDUW of the CCA composite. As the cement content is increased there is an increase in the MDUW of the CCA-S-C composite. For 0% CCA content, on increasing cement content from 0% to 3% and then to 5% the MDUW increases from 17.2 kN/m^3 to 17.4 kN/m^3 and then to 17.5 kN/m^3, respectively. For 10% CCA content, on increasing cement content from 0% to 3% and then to 5% the MDUW increases from 17.6 kN/m^3 to 17.85 kN/m^3 and then to 17.9 kN/m^3, respectively. For 50% CCA content, on increasing cement content from 0% to 3% and then to 5% the MDUW increases from 18.5 kN/m^3 to 19.1 kN/m^3 and then to 19.9 kN/m^3, respectively. For 100% CAA content (0% cement content), the MDUW is 16.9 kN/m^3. For 97% CAA content (3% cement content), the MDUW is 18 kN/m^3. For 95% CAA content (0% cement content), the MDUW is 18.4 kN/m^3. The increase in MDUW of the composite with increasing cement content is due to the filling up of void spaces, thereby making the composite denser. The cement particles are finer than sand as well as CCA, therefore it can easily fill up the void spaces in the CCA-S composite and the CCA only, as well. With more void spaces filled with relatively finer material the composite will get a denser configuration and will increase its MDUW. The lower MDUW value reported for 100% CCA content, which is 16.9 kN/m^3, is because of the absence of finer particles to fill up the void spaces. However, it can be seen that on adding 3% cement content the MDUW value increases to 18 kN/m^3 and with 5% cement content the MDUW value increases to 18.4 kN/m^3.

4.2. CBR test

Figure 7 shows the load-penetration curves obtained from the CBR test. The CCA content, cement content, and curing period significantly affect the load-penetration behaviour of CCA-S-C composite. Figure 7a shows the effect of CCA content on the load-penetration curve of CCA-sand composite. It can be seen from Figure 7a that for 0% CCA content the load-penetration curve shows the elasto-plastic type of behaviour. The curve is initially elastic up to 5 mm penetration and afterward, the behaviour starts shifting towards plastic. Now, as the CCA content is increased the elasto-plastic behaviour starts shifting towards elastic behaviour, especially, when CCA content is increased beyond 30%. The load-carrying capacity also increases as the CCA content is increased unless its content is more than 50%. The load-carrying capacity decreases when 100% CCA content is added to the composite and this value lies between the CCA-S composite containing 30% and 40% CCA content.

Figure 7b shows the load-penetration curve depicting the effect of cement content on the CCA-C composite. It can be inferred from the load-penetration curves that as the cement content increases the load-carrying capacity of the composite increases. Elasto-plastic behaviour has been observed when 0% of cement content is present in the CCA. However, the elasto-plastic behaviour transitioned into a brittle type of behaviour when cement is added. This transition from ductile to brittle behaviour depicts the influence of cement, that is, with cement addition, a mix will become hard and the failure of the composite will be relatively pronounced.

Figure 7c shows the load-penetration curves of CBR tests depicting the effect of the curing period on CCA-C (3% cement content) composite. It can be seen from Fig. 7c that with the increase in the curing period the load-carrying capacity of the CCA-C composite increases significantly. The percent increase in CBR value is 34%, 127%, 183%, and 14%, when the curing period is increased from 0 to 4, 4 to 7, 7 to 14, and 14 to 28 days, respectively. Hence, it can be seen that there is an increasing rate of improvement in CBR value until 14 days, and thereafter, observes a decrease in the rate of improvement. A similar type of trend is observed from the tests conducted when cement is added to the composite. However, in the absence of cement, the results are somewhat different. It is observed that there is a decrease in the CBR value for all types of composites when the curing period increases from 0 to 4 days. The maximum decrease is of the order of 13% when only sand is present, and this decrease in CBR value starts diminishing with the increase in CCA content in the composite. Moreover, this reduction in CBR reaches a constant value of 1% when CCA content approaches 30% and beyond. The reason behind this behaviour maybe lies in the fact that there is unreacted cement adhered to the CCA used in the study [34,35].

<u>Effect of CCA content on CBR</u>

Figure 8 shows the effect of CCA content on the unsoaked and soaked CBR of the composite. The CBR values of CCA-S and CCA-S-C composites keep on increasing until CCA content reaches 50%, and further increasing the CCA content up to maximum, resulting in the reduction of CBR. Moreover, all curing periods show a similar trend.

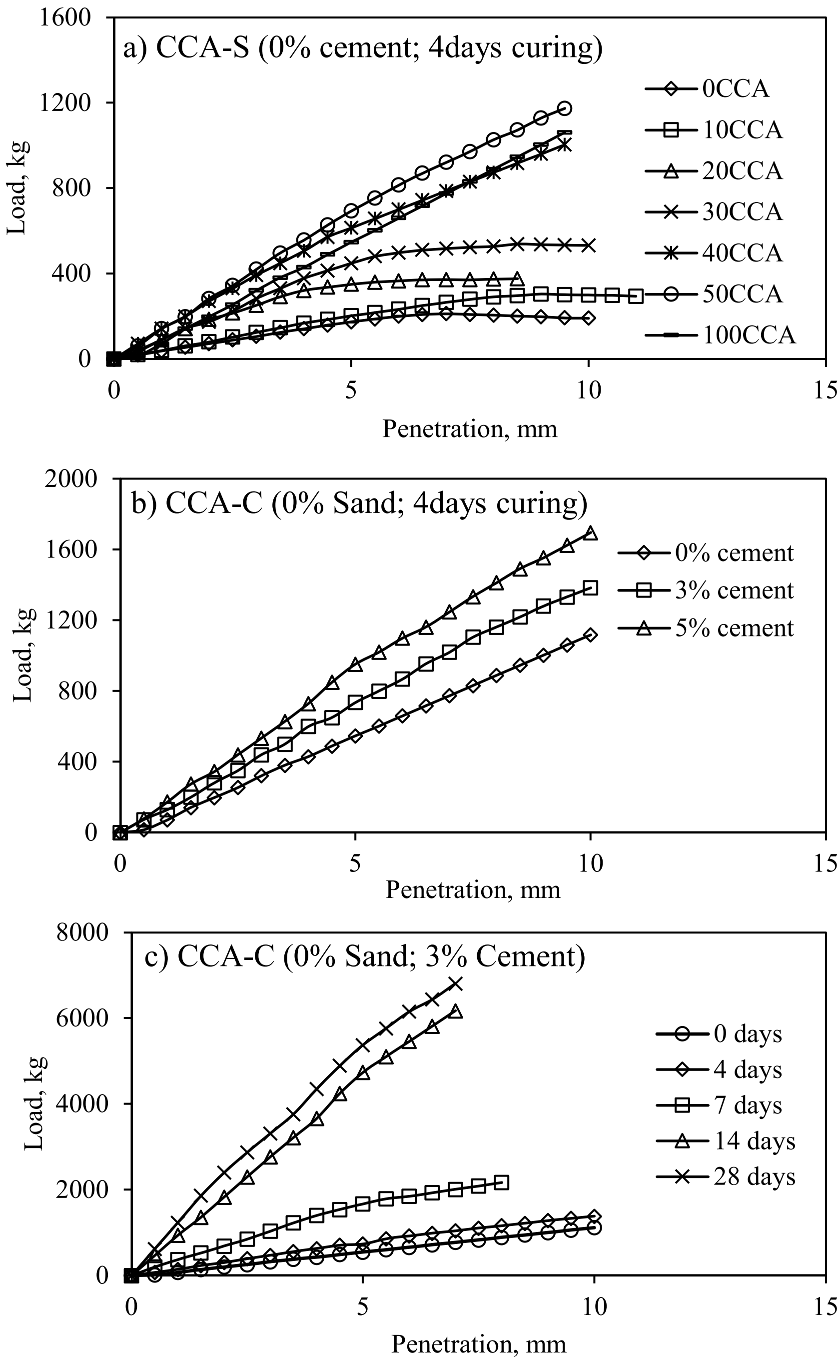

Fig. 7. Load-penetration curves showing the effect of, a) CCA content, b) cement content, and c) curing period

For CCA-S composite (unsoaked), as the CCA content increases from 0% to 50% the CBR value increased from 9.70% to 34.20%, respectively. For 100% CCA content in the composite, the CBR value is 27.37%. For CCA-S-C composite (3% cement content), as the CCA content increases from 0% to 50% the CBR value increases from 8.65% to 44.10%. For 97% CCA and 3% cement content in the composite, the CBR value is 26.60%. For CCA-S-C composite (5% cement content) as the CCA content increases from 0% to 50% the CBR value increases from 9.50% to 38.80%. For 95% CCA and 5% cement content in the composite, the CBR value is 28.30%.

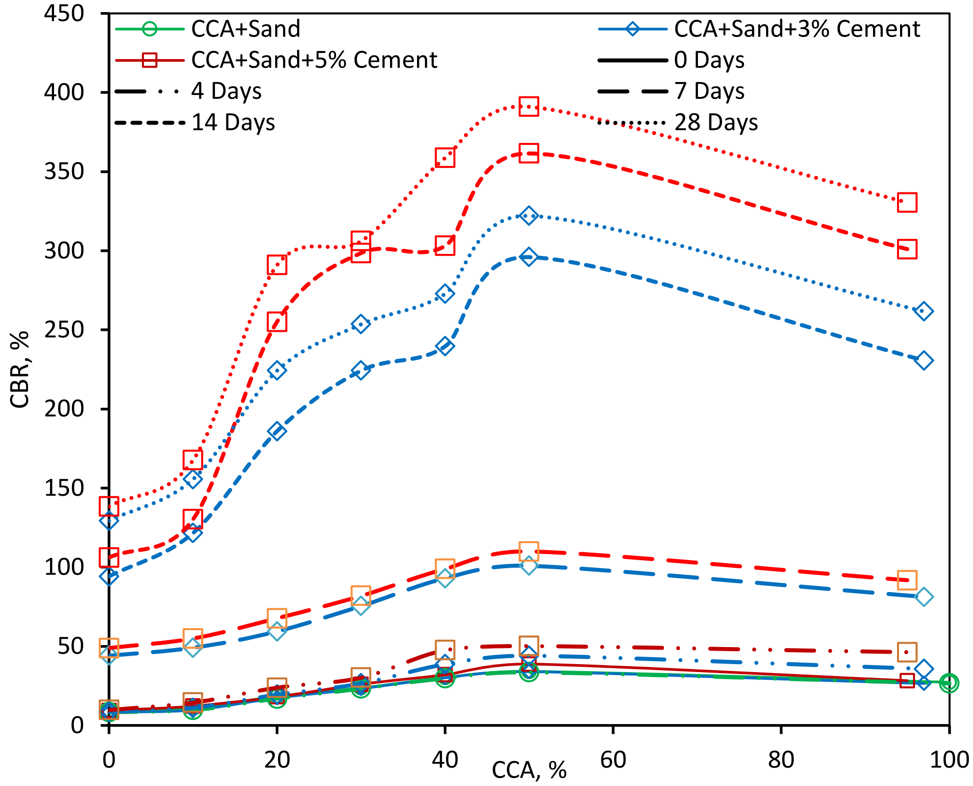

Fig. 8. Effect of CCA content on CBR value of CCA-S-C composite after curing period of 4, 7, 14 and 28 days

Figure 8 also shows the effect of CCA content on the CCA-S and CCA-S-C composite after 4 days of curing. For CCA-S composite, as the CCA content increases from 0% to 50% the CBR value increases from 8.43% to 33.67%, respectively. For 100% CCA content in the composite, the CBR value is 26.60%. For CCA-S-C composite (3% cement content), as the CCA content increases from 0% to 50% the CBR value increases from 8.65% to 44.10%. For 97% CCA and 3% cement content in the composite, the CBR value is 35.80%. For CCA-S-C composite (5% cement content) as the CCA content increases from 0% to 50% the CBR value increases from 9.82% to 50.26%. For 95% CCA and 5% cement content in the composite, the CBR value is 46.35%.

Furthermore, after 28 days of curing period, for CCA-S-C composite (3% cement content) as the CCA content increases from 0% to 50% the CBR value increases from 129.37% to 322.22%. For 97% CCA and 3% cement content in the composite, the CBR value is 261.73%. For CCA-S-C composite (5% cement content) as the CCA content increases from 0% to 50% the CBR value increases from 138.47% to 391.14%. For 95% CCA and 5% cement content in the composite, the CBR value is 330.58%.

The increase in the CBR value of the composite on increasing the CCA content is attributed to the filling up of the void spaces. With more filled-up void spaces, the composite achieves more denser packing and with the denser packing, the composite can take more loading. On further increasing the CCA content, that is beyond 50%, replacement of finer particles takes place and as a consequence resulted in a reduction in finer particles in a composite. With this deficiency, the composite cannot achieve a denser packing, and thereby, results in a poor mix. Hence, this poor mix cannot take as much load than a denser mix.

Effect of curing on CBR

Figure 9 shows the effect of the curing period on the CBR value of the composite. It can be seen from Figure 9 that as the curing period of CCA-S-C composite increases from 0 to 28 days the CBR value increases.

For CCA-S-C composite containing 3% cement content, in the absence of CCA content as the curing period increases from 0 to 28 days, the CBR value of the composite increases from 8.40% to 129.37%. On adding 10% CCA content in the composite the CBR value increases from 9.80% to 155.65% as the curing period increases from 0 to 28 days.

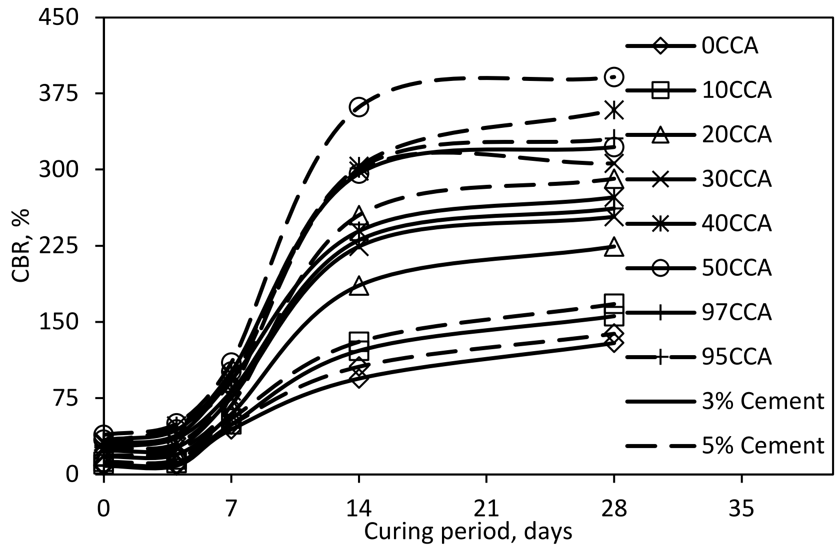

Fig. 9. Effect of curing period on the CBR value of CCA-S-C composite for 3 and 5% cement content

Moreover, by adding 50% CCA content in the composite, its CBR value increases from 34.06% to 322.22% as the curing period increases from 0 to 28 days. When the maximum amount of CCA is added to the composite (97%), its CBR value increases from 26.60% to 261.73% as the curing period increases from 0 to 28 days.

For CCA-S-C composite containing 5% cement content, at 0% CCA content as the curing period increases from 0 to 28 days the CBR value of the composite increases from 9.50% to 138.47%. For 10% CCA content as the curing period increases from 0 to 28 days the CBR value of the composite increases from 12.30% to 167.78%. For 20% CCA content as the curing period increases from 0 to 28 days the CBR value of the composite increases from 18.16% to 291.08%. For 50% CCA content as the curing period increases from 0 to 28 days the CBR value of the composite increases from 38.80% to 391.14%. For 95% CCA content as the curing period increases from 0 to 28 days the CBR value of the composite increases from 28.30% to 330.58%.

The increase in the CBR value of CCA-S-C composite with the increase in the curing period is clearly because of the hydration reaction between cement and water. The composite may consist of two types of cement. One type of cement is the externally added cement (OPC), by weight of the composite, and the other type may be unreacted cement [34,35] present in the mortar adhered on the surface of CCA. On adding water to the composite the hydration reaction between the external cement and water starts. Besides, the hydration reaction between the unreacted adhered cement and water may start and this may lead to an increase in the strength of the composite.

Effect of cement content on CBR

Figure 10 shows the effect of cement content on the CBR value of CCA-S and CCA-S-C composite. It can be inferred from Figure 10 that as the cement content increases in the composite the CBR value increases.

For unsoaked composite, the CBR values of CCA-S and CCA-S-C are almost similar, especially when the cement content is 3%. However, on increasing the cement content to 5%, the CBR value of the composite increases relative to CCA-S and CCA-S-C containing 3% cement content.

The CBR value of the CCA-S and CCA-S-C composite after 4 days of curing, at 0% CCA content in the composite, as the cement content increases from 0% to 3% and then to 5% the CBR value increases from 8.43% to 8.65% and then to 9.82%, respectively. For 50% CCA content in the composite, as the cement content increases from 0% to 3% and then to 5% the CBR value increases from 33.67% to 44.1% and then to 50.26%, respectively. For 100% CCA content (0% cement content), the CBR value is 26.60% and with the addition 3% cement in the CCA (97% CCA content) the CBR value increases to 25.80%. On further adding 5% cement in the CCA (95% CCA content) the CBR value increases to 46.35%. Similar trend can be seen for the 7 and 14 days of curing samples.

In Figure 10 (28 days of curing period), with 0% CCA content as the cement content increases from 3% to 5% the CBR value increases from 129.37% to 138.47%, respectively. With 10% CCA content, as the cement content increases from 3% to 5% the CBR value increases from 155.65% to 167.78%, respectively. For 50% CCA content as the cement content increases from 3% to 5% the CBR value increases

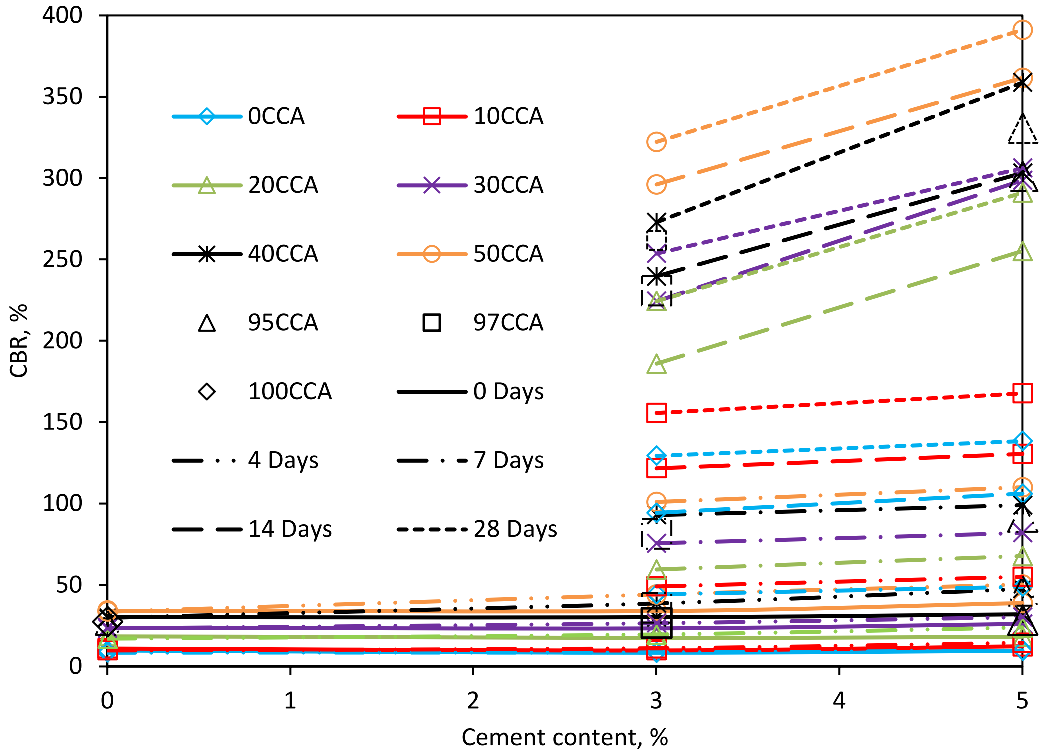

Fig. 10. Effect of cement content on the CBR value of CCA-S and CCA-S-C composite after curing period of 4, 7, 14 and 28 days

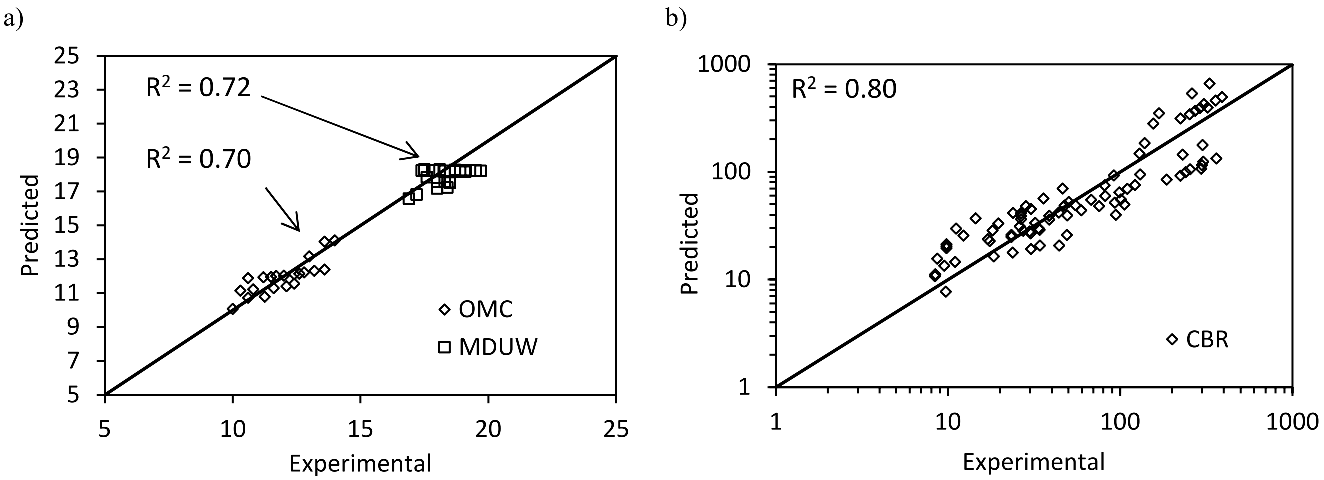

Fig. 11. Comparison of experimental and predicted values for, a) OMC and MDUW; b) CBR

from 322.22% to 391.14%, respectively. However, when the maximum amount of CCA is incorporated in the composite the CBR value increases from 261.73% to 330.58% on increasing the cement content from 3% (97% CCA) to 5% (95% CCA), respectively.

The increase in the CBR value due to the increase in cement content in the composite is an attribution to the denser mix. As the cement content increase, the void space between the sand-sand and sand-CCA particle starts decreasing, and because of the filling of the void spaces, the mix starts gaining denser composition. Hence, the denser the mix the more will be the CBR of the composite.

5. Regression analysis

Regression analyses was carried out on the data obtained from this study, to arrive at empirical expressions which will be useful for obtaining the compaction and strength characteristics of CCA-S and CCA-S-C composites. A power model was adopted for the analysis [36-39]. The dependent parameter being adopted were OMC (%), MDUW (kN/m^3) and CBR (%). The independent parameters being adopted were CCA content (%), sand content (%), cement content (%), and curing period (days). Equations 1, 2 and 3 are the resulting expressions obtained after the regression analyses. In these equations, *S*, *C* and *CP* stand for sand content (%), cement content (%) and curing period (days), respectively. The coefficient of determination (R^2) for Eq. 1, 2 and 3 was 0.70, 0.72 and 0.80, respectively. Figure 11 shows the comparison of the experimental and predicted values using Eqs. 1, 2 and 3, which shows a good agreement between these values.

$$OMC = 12.136.(S)^{0.0160}.(CCA)^{-0.0186}.(C)^{0.0112} \quad (1)$$

$$MDUW = 17.60.(S)^{0.0065}.(CCA)0.0099.(C)^{0.0063} \quad (2)$$

$$CBR = 19.23.(0.995)^{S}.(CCA)^{0.085}.(1.098)^{CP}.(1.112)^{C} \quad (3)$$

6. Conclusions

An experimental study was carried out to study the effect of CCA content, cement content, and curing period on the compaction, load-penetration, and strength behaviour of CCA, CCA-S, CCA-C and CCA-S-C composite. The following conclusions can be drawn from this study:

1. As the CCA content increases from 0% to 50% in CCA-S-C composite the percent decrease in OMC varies from 20% to 22%. On further increasing the CCA content beyond 50% (up to the maximum) and in the absence of cement the percent OMC decrease is 2.9%. However, if the cement is added to the composite the percent OMC either remains the same or increases by an amount of 0.4%. On increasing the CCA content from 0% to 50% in CCA-sand-cement composite the percent increase in MDUW varies from 7.56% to 12.57%. Moreover, if more CCA content is included in the composite the percent reduction in MDUW varies from 5.76% to 8.64%.
2. On increasing cement content from 0% to 5%, the percent increase in OMC varies from 5.7% to 9.6%, if, up to 50% CCA content is present in the composite. On including the maximum amount of CCA content the percent increase in OMC is 12.5%. Similarly, the percent increase in MDUW varies from 1.7% to 7.5% depending on the amount of the CCA content in it, provided, up to 50% CCA content is there in the composite. On further increasing the CCA content to the fullest the percent increase in MDUW is 8.90%.
3. Load-penetration curves show that as the CCA content increases, the elastoplastic behaviour starts shifting towards elastic behaviour, especially, when CCA content increases beyond 30%. With the addition of cement in the CCA-sand composite, the ductile behaviour changes to brittle behaviour. Not much significant change in the load-settlement behaviour was observed if the curing period of the composite is varied.
4. There is an increasing rate of improvement in CBR value, in particular for the composite containing cement, until 14 days of curing, and thereafter, this rate of improvement decreases. However, in the absence of cement, the results are somewhat different, that is, a decrease in the CBR value for all types of composites when curing period increases from 0 to 4 days. The maximum decrease is of the order of 13% when only sand is present, and this decrease in CBR value starts diminishing with the increase in CCA content in the composite. Moreover, this reduction in CBR reaches a constant value of 1% when CCA content approaches 30% and beyond.
5. Percent increase in the CBR value can go up to 412% if the CCA content increases up to 50%. However, the percent reduction in CBR of about 20% can take place if 100% CCA content is used.
6. Percent increase in 4 day CBR value can be as high as 60% if the cement content increases from 0% to 5% in the composite, provided, CCA content is not more than 50%. Moreover, this percent increase in 4 days CBR value can even go up to 74% if the utilization of CCA is maximum. Furthermore, the percent increase in CBR value can go, maximum, up to 37% if cement content increases from 3% to 5%, whatever may be the curing period and CCA content.
7. As the curing period increases from 4 to 7 days the percent increase in the CBR value can reach a maximum value of 411%. Similarly, as the curing period increases from 7days to 14 days the percent increase in CBR value can go up to 276%. Furthermore, the percent increase in CBR value can reach 37% if the curing period increases from 14 to 28 days.
8. Multiple regression analyses show that the coefficient of determination (R^2) is 0.70, 0.72 and 0.80, the

experimental results are in good agreement with the predicted values.

9. It can be concluded based on the compaction and CBR test conducted on CCA only, CCA-S only, CCA-C only, and CCA-S-C composite that the blends of CCA with fractions of cement and sand can prove to be useful for road pavement base or sub-base layer. In India, a minimum CBR value of 30% is required for pavement base or sub-base layer construction [40]. The composite containing the maximum amount of CCA content can be used for pavement base or sub-base layers, as the CBR value is much more than 30%. However, the results obtained are purely dependent on the type of material used in the present study. Hence, it is encouraged that the CCA blended with sand and cement can be used as a pavement base or sub-base layer.

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