



International Journal of Mining and Mineral Engineering

ISSN online: 1754-8918 - ISSN print: 1754-890X

<https://www.inderscience.com/ijmme>

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DOI: [10.1504/IJMME.2025.10070189](https://doi.org/10.1504/IJMME.2025.10070189)

Article History:

Received:	18 May 2024
Last revised:	14 September 2024
Accepted:	16 September 2024
Published online:	08 April 2025

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Ajay Singh Rathore, Manoj Pradhan and
Shirish V. Deo

National Institute of Technology,
Raipur-492010, Chhattisgarh, India
Email: rathoreajaysingh@rediffmail.com
Email: mpradhan@nitrr.ac.in
Email: svdeo.ce@nitrr.ac.in

Vineeth Balakrishnan*

CSIR-Central Institute of Mining and Fuel Research,
Dhanbad-826001, Jharkhand, India
Email: discovervineeth@gmail.com

*Corresponding author

Abstract: The growing demand for sand and the environmental impact of sand mining have prompted efforts to find sustainable alternatives. The Ministry of Environment, Forest, and Climate Change, Government of India, advocates for the use of M-sand and recycled sand in construction to reduce dependency on natural sand. This study explores the potential of coal mine overburden (CMOB) sand as a substitute for natural sand in concrete production. Comprehensive tests, including chemical, petrographic, and physical analyses, were conducted to evaluate CMOB sand's suitability. Concrete mixes with CMOB sand were tested for strength, workability, and durability. Results reveal that CMOB sand can fully replace natural sand without compromising structural integrity. The concrete demonstrated excellent compressive strength, moderate workability, and strong resistance to carbonation, chloride penetration, and acid attacks. This highlights CMOB sand as an eco-friendly, effective alternative, reducing reliance on natural resources while ensuring durable concrete applications.

Keywords: coal mine overburden sand; CMOB; concrete; workability; strength and durability.

Reference to this paper should be made as follows: Rathore, A.S., Pradhan, M., Deo, S.V. and Balakrishnan, V. (2025) 'Coal mine overburden sand as resource material for making cement concrete', *Int. J. Mining and Mineral Engineering*, Vol. 16, No. 1, pp.73–91.

Biographical notes: Ajay Singh Rathore has completed his PhD from National Institute of Technology, Raipur. He has vast experience in the field of civil and environment engineering. He has been working as an Additional Chief Engineer at Chhattisgarh Environment Conservation Board.

Manoj Pradhan is a Professor at Department of Mining Engineering, National Institute of Technology, Raipur. He has expertise in blasting technology. He also has a field experience for five years working in Coal India Ltd. as a

Mining Engineer. He is a life member of various professional bodies of national and international. Till date, he has received two national awards for his work in blasting and has completed numerous sponsored research works in this area.

Shirish V. Deo currently works as a Professor in Department of Civil Engineering, National Institute of Technology Raipur. With multiple years of teaching, research, and extensive experience in RCC structural design, he has successfully completed multiple consultancy and testing projects. Proficient in concrete mix design, project management, and various software applications, he is an associate member of The Institution of Engineers and a life member of ISTE, ACI, and ICI.

Vineeth Balakrishnan is a Senior Scientist in the Mine Planning and Economics Division at CSIRCIMFR, Dhanbad, India. His research specialises in mining engineering, with numerous publications in the field. He is dedicated to driving efficient and sustainable advancements in the mining industry through cutting-edge technologies. He has completed multiple sponsored research projects in the field of Mining Engineering. He has received the 'Chhattisgarh State Young Scientist Award' and the 'Dr. Rajendra Prasad Memorial Award' for his contributions to mining engineering research.

1 Introduction

Opencast coal mining generates a significant volume of overburden, consisting of soil and rock removed to access coal seams. Once the coal is extracted, the overburden is either backfilled into the mined-out area or dumped externally, creating large, uncompacted stacks that disfigure the landscape. These external dumps cause environmental issues like land degradation, air and water pollution, and demand significant land, complicating mine operations. In 2018–2019, India produced 730 million tons of coal, with 90% from opencast mines, leading to the removal of over 1,750 million cubic metres of overburden (Coal Controller's Organization, 2019). While most of this material is backfilled, 20%–25% is dumped externally, requiring 600–700 hectares of land annually.

The increasing demand for coal, coupled with a rising stripping ratio (now as high as 15), results in greater waste rock production. Overburden primarily consists of sandstone and shale, with sandstone comprising up to 85% of the waste (Verma and Deb, 2006). Sandstone composed mostly of quartz and silicate minerals can be processed into fine aggregate for concrete, while the clay from the cementing material can be used for brickmaking. Several studies have explored the potential of utilising overburden waste in construction. For example, Kumar *et al.* (2007) demonstrated the use of crushed sandstone as a fine aggregate in high-performance concrete (HPC), while Jamal and Siddartha (2008) reported superior performance of bricks made from overburden compared to traditional clay bricks. Fontanini *et al.* (2013) and Dos Santos *et al.* (2013) also found that overburden waste could effectively replace fine aggregates in concrete applications.

In light of these findings, a detailed experimental programme was designed to determine the behaviour of the concrete in fresh and hardened stage and to ascertain the use of coal mine overburden (CMOB) sand in cement concrete as fine aggregate.

Concrete is recognised as a dual-phase material, comprising the paste and aggregate phases. The aggregate, acting as an inert filler, occupies a significant volume in concrete, with its composition, arrangement, and dimensions influencing properties such as workability, resilience, strength, mass, and shrinkage. Particle sizes determine the categorisation of aggregates into fine and coarse types; particles passing through a 4.75 mm sieve and retained by a 0.075 mm sieve are considered fine aggregate, while those retained on a 4.75 mm sieve are classified as coarse aggregate. Coarse aggregate serves as an unreactive filler, and the spaces between its particles are filled with fine aggregate, typically represented by sand in concrete (Rathor et al., 2020). Rivers serve as the primary reservoirs of sand; however, the escalating trends of urbanisation, industrial expansion, and population growth have significantly heightened the demand for sand. To address the increased need for natural sand, researchers are exploring alternative materials as substitutes for river sand in concrete as fine aggregate. This study specifically investigates the potential for either complete or partial replacement of natural sand.

Alternative sands fall into three main categories: crushed rock sand, industrial by-product sand, and recycled fine aggregate. Crushed rock sand, commonly known as manufactured sand (m-sand), is produced by crushing virgin rocks. It typically exhibits a more angular shape and coarser surface texture compared to naturally weathered sand particles. The characteristics of crushed rock sand depend on factors such as the type of rock, composition, and the method of production employed (Wang et al., 2014).

Industrial by-products comprise various materials, including blast furnace slag, waste foundry sand, coal bottom ash, cement kiln dust, copper slag, and wood ash. These materials offer potential applications as fine aggregate in concrete (Singh et al., 2018; Dash et al., 2016). However, the challenge with industrial by-products lies in the higher presence of fine particles, which can render concrete more prone to shrinkage, impacting its workability as well (Kirthika et al., 2019).

Recycled fine aggregates originate from the reprocessing of mineral waste materials, predominantly from the construction and demolition (C&D) waste stream (Khatib, 2005). Notable instances of recycled fine aggregates utilised in the construction industry encompass recycled concrete fine aggregate, recycled brick fine aggregate, recycled glass fine aggregate, and recycled bitumen aggregate (Kirthika et al., 2020).

Fine aggregate constitutes up to 30% of the total volume in concrete. As a result, the characteristics of fine aggregate play a crucial role in influencing both the fresh and hardened concrete performance, thereby impacting the cost-effectiveness of concrete. The engineering properties of CMOB sand conform to the specifications outlined for fine aggregate use in concrete, as per the coarse and fine aggregates for concrete – specification (IS Code 383: 2016, 2016). A good concrete should have good workable quality in the plastic stage and should also give required strength and durability in the hardened stage.

2 Details of CMOB sand used

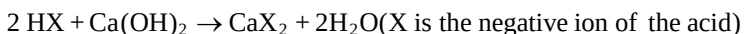
CMOB is sourced from the top sludge horizon of the Parsa (East)-Kanta Basan opencast coal mine, located in the Hasdo-Arand Coalfield in Surguja, Chhattisgarh. Spanning 27.67 km², the block contains geological reserves of 47.86 million tonnes and targets

annual production of 10 MTPA over 50 years. The mine's coal seams (IV, V, VI) range from 1.2 to 8.5 metres thick, with a dipping ratio of 1 in 20, reaching a final depth of 225 metres. The total minable reserve is 452.46 MT, requiring 2,334.63 million cubic metres of overburden removal at a 5.16 overall stripping ratio.

The Talchir formation rests on an uneven Precambrian metamorphic basement, marked by a significant unconformity, with a maximum thickness of 14.28 metres. Lithologically, it consists of fine-grained, well-sorted but poorly matured light green to green sandstone and siltstone. Examination of borehole lithologs from the block reveals that sandstone is the dominant coal measure rock. Up to a depth of about 26 metres, the rock formation is composed of poorly consolidated, weathered fine to coarse-grained sandstone, transitioning to harder rock below. Between 26 and 56 metres, the formation predominantly consists of medium to coarse-grained sandstone.

Based on the investigation carried out on CMOB sand, it can be said that CMOB sand recovered from the top sludge horizon of overburden of the coal mine is comparable with the river sand of Mahanadi River and can be used in concrete as fine aggregate (Rathor et al., 2020). The particle shape, texture, and gradation wise, CMOB sand slightly differs from river sand. Microscopic examination of the CMOB sand revealed that particles are partly rounded with rough surface texture, whereas the particles of the river sand were found to be rounded with smooth texture. The distribution of particle sizes affirms that CMOB sand aligns with grading zone III. It possesses a loose bulk density of 1,591 kg/m³ under saturated and surface dry conditions, while its compacted bulk density is 1,812 kg/m³. The specific gravity measures at 2.6, with a water absorption rate of 1.2%. The primary constituents of CMOB sand consist of approximately 90.0% SiO₂ and around 4.0% Al₂O₃. Notably, the levels of harmful substances within CMOB sand adhere to the limits stipulated by the IS code.

Concrete exhibits alkaline properties, which render it vulnerable to acid corrosion. Among the numerous acids capable of damaging concrete, sulphuric acid stands out as one of the most potent and destructive. Its impact on concrete structures can range from significant deterioration to outright damage, contingent upon its concentration and mode of formation (Joorabchian, 2010). Sulphuric acid may be found or generated in various environments surrounding concrete infrastructure, including underground water, industrial waste, acid rain, and subterranean sewer systems. When concrete comes into contact with acid, the cement paste component undergoes disintegration. Most pronounced is the dissolution of calcium hydroxide which occurs according to the following reaction:



The decomposition of the concrete depends on the porosity of the cement paste, concentration of the acid, the solubility of the acid calcium salts (CaX₂), and on the fluid transport via the concrete conduits. Insoluble calcium salts may percolate in the voids and can slow down the attack (Naseeruddin et al., 2019).

3 Material and methods

3.1 Mix used

Samples collected from the coal mine were mixed and crushed to break clumps. Using sedimentation and decantation, sand was separated from clay. Overburden was soaked in water, stirred to form a clay-water suspension, and carefully decanted, leaving sand at the bottom. The process was repeated until clear water remained. The sand was sun-dried and termed CMOB sand.

Table 1 Concrete mix proportion for water-cement ratio 0.48

Mix	Cement (kg)	Natural sand (kg)	CMOB sand (kg)	20 mm course aggregate (kg)	10 mm course aggregate (kg)	Water (kg)	Super plasticizer (g)
CC ₁₀₀₋₀	5.78	11.44	0	13.325	7.662	2.789	41
CC ₇₅₋₂₅	5.78	8.58	2.86	13.325	7.662	2.789	41
CC ₅₀₋₅₀	5.78	5.72	5.72	13.325	7.662	2.789	41
CC ₂₅₋₇₅	5.78	2.86	8.58	13.325	7.662	2.789	41
CC ₀₋₁₀₀	5.78	0	11.44	13.325	7.662	2.789	41

Table 2 Concrete mix proportion for water-cement ratio 0.43

Mix	Cement (kg)	Natural sand (kg)	CMOB sand (kg)	20 mm course aggregate (kg)	10 mm course aggregate (kg)	Water (kg)	Super plasticizer (g)
CC ₁₀₀₋₀	6.46	11.380	0	13.251	7.619	2.769	46
CC ₇₅₋₂₅	6.46	8.535	2.845	13.251	7.619	2.769	46
CC ₅₀₋₅₀	6.46	5.690	5.690	13.251	7.619	2.769	46
CC ₂₅₋₇₅	6.46	2.845	8.535	13.251	7.619	2.769	46
CC ₀₋₁₀₀	6.46	0	11.380	13.251	7.619	2.769	46

Table 3 Concrete mix proportion for water-cement ratio 0.37

Mix	Cement (kg)	Natural sand (kg)	CMOB sand (kg)	20 mm course aggregate (kg)	10 mm course aggregate (kg)	Water (kg)	Super plasticizer (g)
CC ₁₀₀₋₀ (control mix)	7.23	10.903	0	13.373	7.502	2.711	52
CC ₇₅₋₂₅	7.23	8.178	2.725	13.373	7.502	2.711	52
CC ₅₀₋₅₀	7.23	5.452	5.451	13.373	7.502	2.711	52
CC ₂₅₋₇₅	7.23	2.725	8.178	13.373	7.502	2.711	52

To investigate the effect of replacing natural sand by CMOB sand on workability, strength, and durability of the concrete, mixes were prepared for water-cement ratio of 0.48, 0.43 and 0.37. Selected water-cement ratios are generally used in various local construction works. Concrete mixes were prepared by using OPC cement, replacing the locally available natural sand with 25%, 50%, 75% and 100% CMOB sand and using

locally available coarse aggregate. One control concrete mix was also prepared for each water-cement ratio of 0.48, 0.43 and 0.37 with 100% locally available natural sand. Mixes were designated as CC₁₀₀₋₀, CC₇₅₋₂₅, CC₅₀₋₅₀, CC₂₅₋₇₅ and CC₀₋₁₀₀ representing 100% natural sand, 75% natural sand and 25% CMOB sand, 50% natural sand and 50% CMOB sand, 75% natural sand and 25% CMOB sand and 100% CMOB sand respectively. The details of the concrete mix proportion used in the study for water-cement ratios 0.48, 0.43 and 0.37 are presented in Table 1, Table 2 and Table 3 respectively.

3.2 Preparation of concrete specimens

The required quantities of cement, natural sand, CMOB sand, coarse aggregate (20 mm and 10 mm) was weighed and kept separately in different pans. A weighed quantity of water and super plasticizer were taken in separate containers. Firstly, coarse aggregate and fine aggregate were poured into the mixer and mixed for three to four minutes. Then cement was poured inside the mixer and mixed for another two minutes. For proper mixing, about half quantity of weighed water was added to concrete and it was mixed for two minutes. The remaining quantity of water with super plasticizer was added and concrete was mixed for further two to four minutes till a uniform coloured and homogeneous concrete was obtained. Then, the mixed material (fresh concrete) was out poured on a metal tray. Slum test was carried out on fresh concrete, and cubes and beams were casted for strength and durability tests. The cube and beam moulds were filled with concrete and adequately vibrated for one to two minutes on vibration table. After casting and compaction, top of all the moulds of cube and beam were finished with a steel trowel. Then, casted moulds were covered with wet gunny bags at room temperature for 24 hours. After 24 hours, moulds were demoulded and all the cube and beam specimens casted were kept for curing in a water tank.

3.3 Bulk electrical resistivity test

The electrical resistivity test was conducted on 28-days cured concrete cubes specimen of different mixes as per the procedure laid down in ASTM C1760-12 (2012). The test was carried on three specimens for each mix proportion and the average of the three observations is reported as the electrical resistivity of the concrete mix.

3.4 Carbonation

The carbonation resistance of concrete cubes is evaluated by measuring carbonation depth of the cube specimens under the action of CO₂. The 28-days aged cubical specimens of all the five concrete mixes were left to surface dry in normal temperature and then kept in carbonation chamber at 35°C temperature, 70% humidity and 5% CO₂. After carbonation period of 28 days, the specimens were taken out from the chamber and broken into two halves. A spray of 1.0% solution of phenolphthalein indicator was applied on the freshly broken surface of the concrete to find the area affected by the carbonation. After few minutes, un-carbonated portion of broken concrete cube, where phenolphthalein solution was applied, turned into pink colour. The carbonation depth was measured by using a measuring scale. The tests were performed on three specimens of

each concrete mix used, and the average value of carbonation depth of three specimens was reported as carbonation depth of that mix.

3.5 *Ultrasonic pulse velocity (UPV)*

UPV test was conducted on the same specimens on which electrical resistivity tests was conducted. The specimens were left in the open atmosphere for drying before conducting the pulse velocity tests.

3.6 *Sulphuric acid attack*

The durability of concrete in terms of resistance to sulphuric acid was evaluated by placing the 28-days cured cubical specimens of all the five concrete mixes used in the study under the action of 5% sulphuric acid for 28 days. The samples dried at normal temperature were again dried in the oven at 100°C till a constant mass is obtained. Mass of each specimen was noted and then the specimens were kept in 5% sulphuric acid solution bath for 28 days. The pH value of the acidic media was at 0.3. The pH value was periodically checked and maintained at 0.3 by adding required quantity of concentrated sulphuric acid. After 28 days of immersing in acid solution, the specimens were taken out, washed in running water, and then kept in atmosphere to dry at room temperature. Subsequently, they were dried in the oven at 100°C till constant mass was obtained. Mass of each specimen was again noted.

3.7 *Water absorption test*

Durability of concrete in terms of water absorption become important when concrete is to be used for under water structures. Three specimens of each concrete mix were dried in oven at 100°C to 110°C for at least 24 hours. Specimens were allowed to cool in dry air to a temperature of 20°C to 25°C after removing from the oven and mass was determined. The above procedure was repeated till constant mass is obtained ensuring evaporation of all the water present in their pores. The specimens, after being dried in an oven, were subsequently submerged in water at around 21°C for a minimum of 48 hours, ensuring that two consecutive measurements of the mass of the surface-dried specimen, taken at 24-hour intervals, indicated an augmentation in mass that was less than 0.5% of the larger recorded value. To prepare the specimens for measurement, surface moisture was removed using a towel, and their mass was measured. The percentage increase in mass was then calculated.

4 **Result and discussion**

4.1 *Workability test*

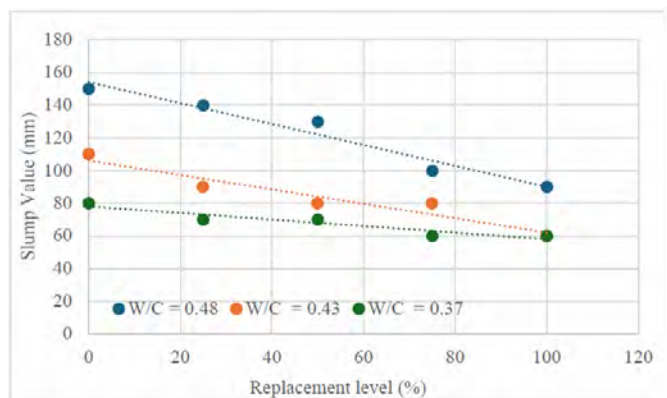
The term ‘workability’ in concrete refers to how easily freshly mixed concrete can be blended, positioned, compacted, and finished without significant loss of uniformity. This property gauges the flow or mobility of concrete and has a direct impact on strength, quality, appearance, and even labour costs associated with placement and finishing tasks. Three key factors primarily influence the workability of concrete: the water-cement ratio,

the shape and size of aggregates, and the use of admixtures. Various tests, including the slump cone test, compacting factor test, vee-bee consistometer test, and Kelly ball test, are employed to assess concrete workability.

For the purposes of this study, the slump cone test was utilised to gauge the workability of the concrete mixes. The result of the slump cone test provides insight into how a compacted, inverted cone of concrete behaves when subjected to gravity. This test quantifies the consistency or wetness of the concrete, thereby offering a perspective on the workability status of the concrete mixture. Slump cone test was conducted on all the five concrete mixes prepared with water-cement ratio 0.48, 0.43, and 0.37.

The slump value of the control mix [CC₁₀₀₋₀] for the three-water cement ratio used in the study, i.e., 0.48, 0.43, and 0.37 was found to be 150 mm, 110 mm, and 80 mm, respectively and the corresponding slump values at 100% replacement level [CC₀₋₁₀₀] were found 90 mm, 60 mm, and 60 mm, respectively; about 40%, 45%, and 25%, respectively lower than the corresponding value of control mix. As expected, all the mixes prepared with water-cement ratio of 0.48 exhibited highest slump values followed by the corresponding mixes prepared with water-cement ratio of 0.43 and 0.37. The variation in slump value with different sand replacement level is shown in Figure 1.

Figure 1 Variation of slump value of concrete with sand replacement level (see online version for colours)



It can be seen from Figure 1, that slump value of all the three water-cement ratios used in the study decreased linearly with increase in replacement level of sand. The slope of the trend line for water-cement ratio 0.48 is having highest negative slope followed by the trend line for water-cement ratios 0.43 and 0.37. This indicates that the sand replacement level has cumbersome effect on the slump values of the mixes prepared with water-cement ratio 0.48. The slope of the trend lines become milder as the water-cement ratio reduces, implying that influence of replacement level of sand reduces as the water-cement ratio reduces. CMOB sand differs from river Mahanadi sand in terms of shape, surface texture, and gradation. The reduction the slump value of the mixes prepared with increasing percentage of CMOB sand can be attributed to the partly rounded shape and rougher texture, and comparatively poor gradation of the particles of CMOB sand than the natural sand. River sand has rounded particles with smooth texture and hence develop less inter particle friction than CMOB sand which makes it more

workable. Water acts as a lubricant; higher water-cement ratio helps in the easy movement of particles and hence provides more workability to the concrete.

As per the IS Code 456:2000 (2000), the slump value of the concrete prepared with CMOB sand [mix CC₀₋₁₀₀] for all the three water cement ratios used in the study, lies in between 60 mm to 90 mm and hence, the workability of CMOB concrete can be said medium and it can be used for construction of heavily reinforced sections in slabs, beams, walls, column, and slipform works.

4.2 Strength test

Compressive strength provides the load bearing capacity to the concrete structure. It is influenced by several factors including quality and quantity of cement, coarse and fine aggregate, mixing level and compaction, environment condition and water cement ratio.

Seven-days and 28-days compressive strength of the specimens prepared with all the five types of mixes with all the three water-cement ratios were determined and the average value of three specimens is reported as compressive strength of the mix.

It is observed from the test results that both seven-days and 28-days compressive strength of the concrete mix used, increased with increase in the sand replacement level for all the three water-cement ratios used in the study. 28-days compressive strength at 100% sand replacement level (CC₀₋₁₀₀) was found to be 7.97%, 8.39%, and 6.84% higher than that of the compressive strength of the control mix (CC₁₀₀₋₀) for water-cement ratio 0.48, 0.43 and, 0.37, respectively. As expected, both seven-days and 28-days compressive strength of all the control mix design used in the study was found to be increased with lowering of water-cement ratio.

Improvement in the compressive strength with increase in the replacement level can be attributed to combined effect of the difference in the shape, surface texture, fineness modulus and size distribution of the CMOB sand particles with river sand. As stated earlier, the particles of the river sand were round with smooth surface whereas particles of the CMOB sand were found partly rounded with comparatively rough surface. Angular particles not only exhibit a better interlocking effect in concrete, but also, have a higher specific surface area than the smooth and rounded particles and hence may show higher bond strength than the rounded particles. The CMOB sand is observed finer than the river sand used and hence, offers more surface area for bonding with hydrated cement paste than river sand is also responsible for increase in compressive strength with increase in replacement level of sand.

The variation in seven-days and 28-days compressive strength with different sand replacement level is shown in Figures 2 and 3 respectively. The trend line for variation in seven-days compressive strength with replacement level, for water-cement ratio 0.37 is having marginally higher positive slope than all other trend lines which are having almost same slope.

Flexural strength is a measure of the tensile strength of concrete. It gauges the resistance of unreinforced concrete beam or slab in bending. The deflection and cracking behaviour of concrete structure depend on the flexural tensile strength of concrete (Ahmad et al., 2014). It is an essential property in structural concrete design because it affects the flexural cracking, shear strength, deflection characteristics and brittleness ratio of concrete (Meisuh et al., 2018). Twenty-eight-days flexural strength of the beam shaped specimens prepared with all the five types of mixes was determined and the average

value of three specimens is reported as the flexural strength of the mix. Figure 4 shows measurement of flexural strength of concrete beam specimen.

Figure 2 Variation of seven-days compressive strength of concrete with sand replacement level (see online version for colours)

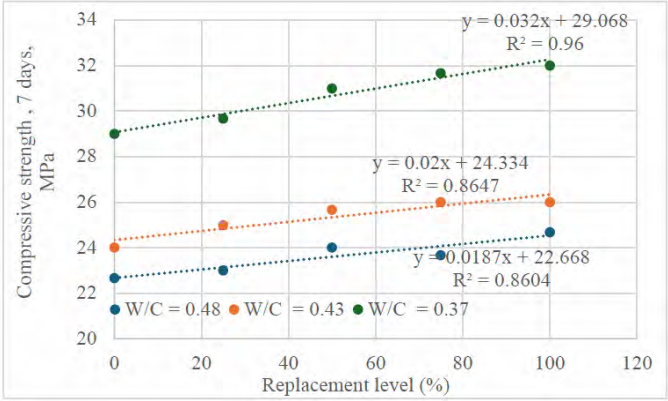
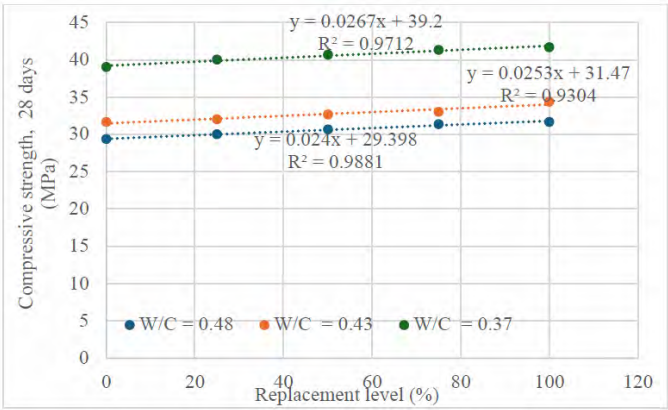


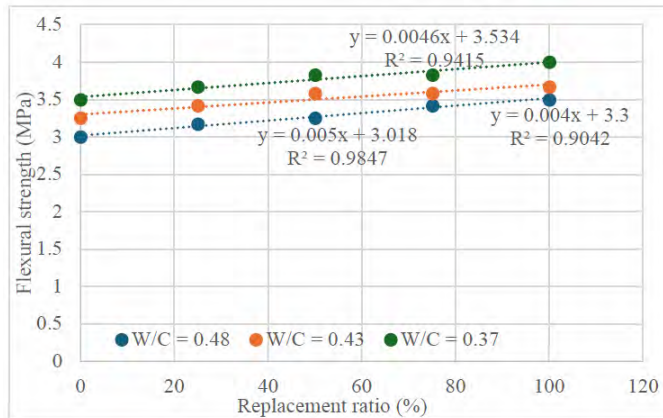
Figure 3 Variation of 28-days compressive strength of concrete with sand replacement level (see online version for colours)



Like compressive strength, 28-days flexural strength of the concrete mix used also increased with increase in the sand replacement level for all the three water-cement ratios used in the study. The flexural strength of the control mix [CC₁₀₀₋₀] for the three-water cement ratio used in the study, i.e., 0.48, 0.43, and 0.37 was found to be 3.0 MPa, 3.25 MPa, and 3.5 MPa, respectively and the corresponding values of the CMOB sand concrete [100% replacement level, mix CC₀₋₁₀₀] were found 3.5 MPa, 3.67 MPa and 4.0 MPa, respectively; about 16.6%, 12.9%, and 14.3%, respectively higher than the corresponding value of control mix. Like compressive strength, all the mixes prepared with water-cement ratio of 0.37 also exhibited highest flexural strength values followed by the corresponding mixes prepared with water-cement ratio of 0.43 and 0.48.

Flexural strength for all the three water-cement ratios used in the study increased linearly with increase in replacement level. The slope of the trend lines for all the three water-cement ratios is similar.

Figure 4 Variation of 28-days flexural strength of concrete with sand replacement level (see online version for colours)



Flexural strength is traditionally defined as a function of compressive strength and is usually approximated as 10% to 15% of the compressive strength (Meisuh et al., 2018). The CMOB sand also follow 10%–15% thumb rule for estimation of flexural strength.

4.3 Bulk resistivity

Figure 5 shows variation of bulk electrical resistivity values of concrete with sand replacement level. The bulk resistivity of the control mix [CC₁₀₀₋₀] for water-cement ratio 0.48, 0.43, and 0.37 is found to be 10.5, 11.3, and 13.6 kΩ-cm, respectively and the corresponding values at 100% replacement level [CC₀₋₁₀₀] were found 11.6, 15.0, and 19.4 kΩ cm, respectively; about 10.5%, 32.8%, and 42.6%, respectively higher than the corresponding value of control mix.

The bulk electrical resistivity for all the three water-cement ratios used in the study increased linearly with increase in replacement level. The slope of the trend line for water-cement ratio 0.37 is having highest positive slope followed by the trend line for water-cement ratios 0.43 and 0.48. This implies that at water cement ratio of 0.37, sand replacement level has a strong bearing on bulk resistivity, however as the water-cement ratio increases, the effect becomes lesser and lesser, and the trend line became almost flat at water-cement ratio of 0.48.

Reinforced concrete structures are sometimes exposed to severe environment during their service period. Preserving such structure without refurbishing is a difficult task for structure designers (Stanish et al., 1997). Chloride ingress is one of the leading causes of corrosion of reinforced concrete structures in chloride polluted environments (Kim et al., 2016). Chloride destroys the reinforcing steel and reduces the life of the structure (Stanish et al., 1997). Chloride sources may be external such as seawater, de-icing salts, and salt spray or may be internal such as chlorides from concrete mixing (Nguyen et al., 2017). Concrete safeguards the reinforcing steel in such environments and hence, it is

important to know the resistance of concrete to chloride ingress. The penetration of chloride ions into concrete is a complex nonlinear dynamic phenomenon which can take place by means of ionic diffusion, capillary sorption, permeation, dispersion, etc. (Earlin and Verbeck, 1975; Neville, 2011). The permeability of concrete primarily hinges on its microstructural attributes, including the distribution of pore sizes and the configuration of interconnections among them. A microstructure characterised by smaller pores and reduced connectivity corresponds to diminished permeability. Conversely, a porous microstructure marked by a greater extent of interconnections translates to heightened permeability and an elevated propensity for chloride ingress in most cases (Layssi et al., 2015). Chloride penetrability classification (Thomas et al., 2018) based on bulk resistivity is presented in Table 4. It is evident from the table that both river sand concrete and CMOB sand concrete fall under low chloride penetrability class. CMOB sand concrete can be said durable and can be safely used in construction of civil structures having long life or that need to be constructed in chloride-laden environment.

Figure 5 Variation of bulk electrical resistivity values of concrete with sand replacement level (see online version for colours)

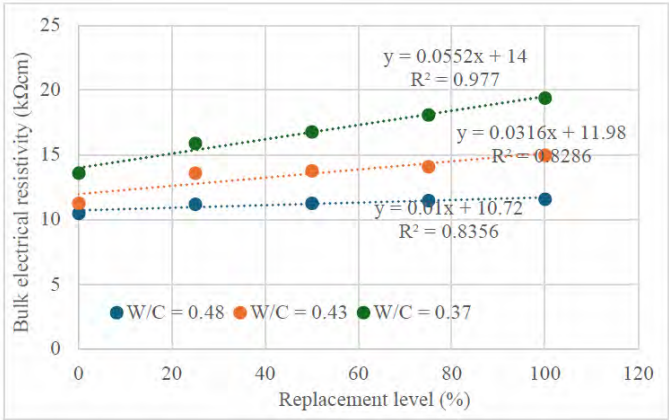


Table 4 Chloride penetrability classification based on bulk resistivity

Chloride penetrability	Bulk resistivity, kΩ-cm
High	< 5
Moderate	5–10
Low	10–20
Very low	20–200
Negligible	> 200

Source: Thomas et al. (2018)

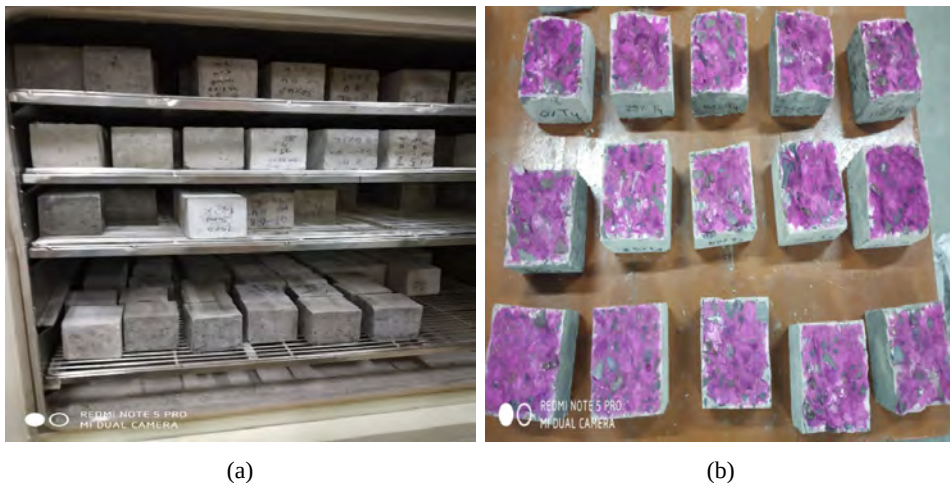
4.4 Carbonation

Carbonation is a significant factor that adversely impacts the durability of reinforced concrete. Concrete naturally maintains a robust alkaline environment with a pH range of approximately 12–13, owing to the presence of calcium hydroxide within its structure. This alkalinity contributes to the formation of a protective passive film on steel

reinforcement bars, shielding them from corrosion. However, when atmospheric carbon dioxide gas permeates the concrete, it interacts with the calcium hydroxide, leading to a reduction in the concrete's pH. This chemical transformation is referred to as carbonation. As carbonation progresses, the decreased alkalinity eventually reaches the steel reinforcement. At this juncture, the protective passive film encompassing the steel is compromised, initiating the corrosion process of the steel bars (Papadakis et al., 1991; Neville, 1996; Cho et al., 2016). To check carbonation-induced corrosion susceptibility of the concrete, carbonation testing is performed.

The carbonation process of concrete involves various physical and chemical processes. The carbon dioxide is present in the atmosphere. The instrumental mechanism of carbonation is the reaction of diffused CO_2 with calcium hydroxide. The diffusion of CO_2 is dependent upon transport properties of concrete structure. These transport properties are governed by several factors including moisture content, type of cement and temperature of the media. Figure 6(a) shows test set-up for carbonation effect, and 6(b) shows determination of carbonation effect.

Figure 6 (a) Test set-up for carbonation effect, and (b) Determination of carbonation effect (see online version for colours)



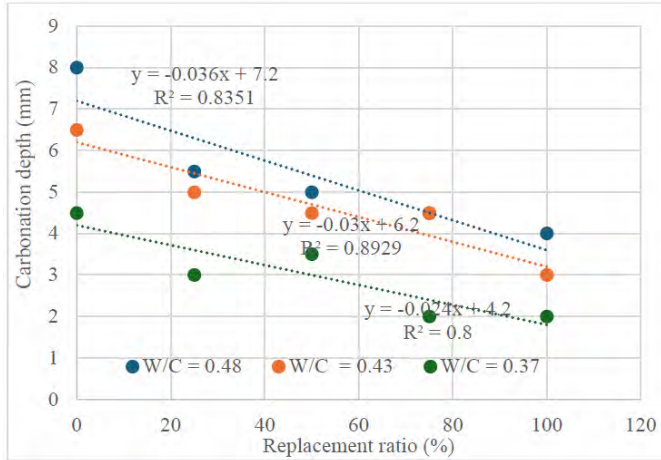
The carbonation depth of the control mix [CC_{100-0}] for the three-water cement ratios used in the study, i.e., 0.48, 0.43, and 0.37 was found to be 8.0 mm, 6.5 mm, and 4.5 mm, respectively and the corresponding values at 100% replacement level [CC_{0-100}] were found, 4.0 mm, 3.0 mm, and 2.0 mm, respectively; about 50%, 53.85%, and 55.55%, respectively lower than the corresponding value of control mix. The low carbonation depth of CMOB sand concrete [CC_{0-100}] may be due to its higher bulk density which implies that particles of CMOB sand are densely packed in the concrete and are allowing limited air movement as compared to particles of river sand.

The variation in carbonation depth with different sand replacement level is shown in Figure 7.

The carbonation depth for all the three-water cement ratio used in the study decreased linearly with increase in replacement level. The slope of the trend line for water-cement

ratio 0.48 is having highest negative slope followed by trend line of water-cement ratio 0.43 and 0.37.

Figure 7 Variation of carbonation depth of concrete mixes with sand replacement level (see online version for colours)



The test revealed that in terms of carbonation, concrete prepared with CMOB sand at all replacement level and all water cement ratios, is more durable the concrete prepared with natural river sand.

4.5 Ultrasonic pulse velocity

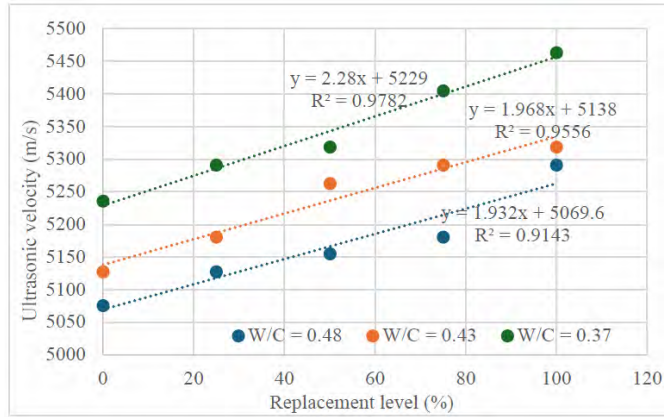
The UPV test is employed to assess uniformity and identify internal flaws such as cracks and segregation within concrete. The procedure involves the transmission of ultrasonic pulse waves through the concrete specimen. As the pulse traverses the material, it undergoes multiple reflections at the boundaries of different material phases within the concrete, giving rise to a complex system of stress waves that includes longitudinal, transverse, and surface waves.

The velocity of the pulse wave is contingent upon the quality of the concrete, considering factors such as density, homogeneity, and uniformity. High-quality concrete typically exhibits a higher pulse velocity, indicating a more homogeneous and uniform structure. Conversely, poor-quality concrete characterised by the presence of cracks, voids, and internal flaws tends to attenuate the strength of the transmitted pulse. Therefore, the UPV test serves as a valuable tool for non-destructive evaluation, offering insights into the integrity and quality of the concrete structure.

The UPV of three specimens for each mix was determined and the averages of the three specimens were reported as the UPV of the concrete mix.

The UPV value of the control mix [CC₁₀₀₋₀] for the three-water cement ratios used in the study, i.e., 0.48, 0.43, and 0.37 was found to be 5,076 m/s, 5,128 m/s, and 5,236 m/s, respectively and the corresponding values at 100% replacement level [CC₀₋₁₀₀] were found, 5,291 m/s, 5,319 m/s, and 5,464 m/s, respectively; about 4.2%, 3.7%, and 4.3%, respectively higher than the corresponding value of control mix. The tests results are graphically presented in Figure 8.

Figure 8 Variation of UPV of concrete mixes with sand replacement level (see online version for colours)



The UPV value for all the three water-cement ratios used in the study increased linearly with increase in replacement level. The slope of the trend line for all the three water-cement ratios used in the study is almost same. IS Code 13311 (Part 1) (1992) suggest the UPV criteria for evaluating the quality of the concrete as given in Table 5.

Table 5 UPV criteria for concrete quality grading

S. no.	Pulse velocity (km/s)	Concrete quality grading
1	Above 4.5	Excellent
2	3.5–4.5	Good
3	3.0–3.5	Medium
4	Below 3.0	Doubtful

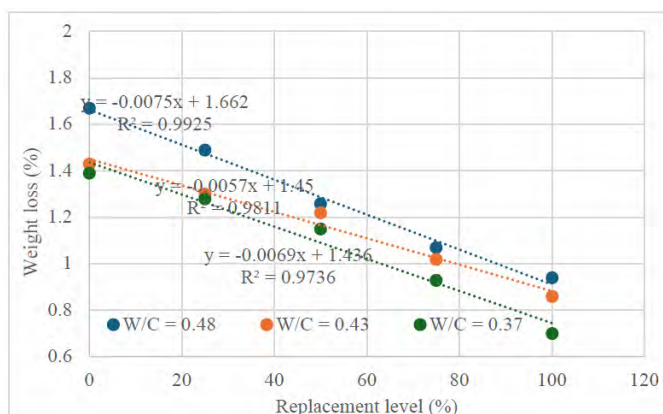
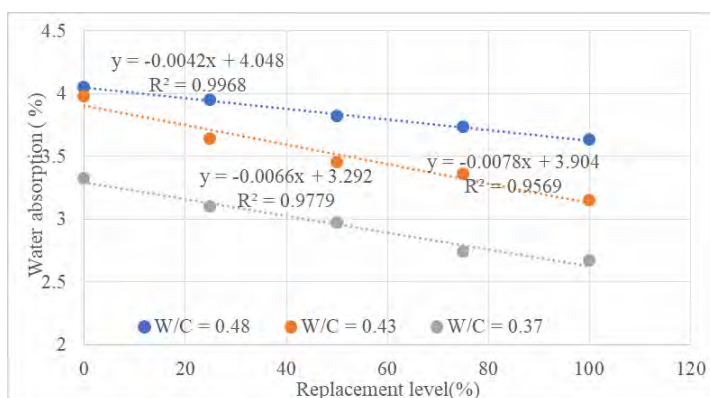
Source: IS Code 13311 (Part 1) (1992)

The UPV value of all the concrete mix used in the study was found above 5,000 km/s and falls under excellent quality. The UPV CMOB sand concrete [CC₀₋₁₀₀] is marginally better than control mix [CC₁₀₀₋₀].

4.6 Sulphuric acid attack test

The acid attack in three specimens for each mix was determined and the averages of the three specimens were reported. The mass loss of the control mix [CC₁₀₀₋₀] for water-cement ratio 0.48, 0.43, and 0.37 is found to be 1.67%, 1.43%, and 1.39%, respectively and the corresponding values at 100% replacement level [CC₀₋₁₀₀] were found 0.94%, 0.86%, and 0.70%, respectively; about 43.7%, 39.87%, and 49.64%, respectively higher in the corresponding value of control mix. The tests results are graphically presented in Figure 9.

The mass loss due to sulphuric acid attack for all the three water-cement ratios used in the study decreased linearly with increase in replacement level. The slope of the trend line for water-cement ratio 0.37 and 0.48 is similar and higher than that of the trend line for water-cement ratio 0.43.

Figure 9 Variation in weight loss due to acid attack of concrete mixes with sand replacement level (see online version for colours)**Figure 10** Variation in water absorption percentage of concrete mixes with sand replacement level (see online version for colours)

4.7 Water absorption test

Average mass gain of three specimens for each concrete mix was reported as water absorption of the mix. It can be seen in the table that the water absorption decreased with increase in the replacement level of sand in all the three water-cement ratios used. The maximum absorption was observed at water-cement ratio of 0.48 followed by 0.43 and 0.37. The tests results are graphically presented in Figure 10. The slope of the trend line for water cement ratio 0.43 is having highest negative slope followed by the trend line for water cement ratios 0.48 and 0.37.

5 Conclusions

The concrete specimens prepared with CMOB sand demonstrated excellent performance in terms of workability, strength, and durability. Cement mortar prepared with 100%

CMOB sand exhibited 10.2% higher 28-days compressive strength than that of the control mix. Though, the workability of the CMOB sand concrete was found lower than that of the control mix, but for all the three water-cement ratios used in the study, it was found between 60 mm–90 mm, implying that CMOB sand concrete is of medium workable degree. Regarding, strength both compressive and flexural strength was observed higher of CMOB sand concrete than of control mix concrete. Bulk electrical resistivity of CMOB sand concrete for water-cement ratio 0.48, 0.43 and, 0.37 was noted 11.6, 15.0, and 19.4 k Ω -cm, respectively with the corresponding values for control mix concrete were 10.5, 11.3, and 13.6 k Ω -cm, respectively. This implies that from chloride ingress point of view, CMOB sand makes a better concrete than natural sand and shall provide a better durability to reinforced concrete in chloride loaded environment. Carbonation is another major cause that affects the durability of reinforced concrete. Carbonation depth in CMOB sand concrete for all the three water-cement ratios was observed about 50% of that found in control mix concrete. UPV of both CMOB sand concrete and control concrete was found above 5,000 m/s, confirming excellent quality of concrete. CMOB sand concrete was found better than control mix concrete in terms of both sulphuric acid attack and water absorption. Mass loss due to sulphuric acid attack was about 40% to 50% higher in control mix concrete than in CMOB sand concrete for all the three water-cement ratios used in the study. Less water absorption has been noted in CMOB concrete than in control mix concrete in all the three water cement ratio mixes used.

Based on above investigations, it can be said that CMOB sand can be used as a 100% replacement of natural sand in concrete. The concrete prepared using CMOB sand will offer a good strength, medium workability, and excellent durability in terms of carbonation, chloride ingress, sulphuric acid attack and water absorption.

Acknowledgements

The authors want to acknowledge the managements of the M/S Rajasthan Rajya Vidyut Utpadan Nigam, for granting permission to collect samples and providing necessary information. The authors also want to acknowledge the director of the National Institute of Technology (Raipur, India) for providing the necessary support to carry out the laboratory experiments.

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