Performance evaluation of controlled low-strength blended cement concrete modified with recycled waste materials

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Abstract

Purpose – This work aims to investigate the feasibility of recycling waste plastic (polyethylene terephthalate) as a coarse aggregate for producing blended cement concrete modified with fly ash and pond ash.

Design/methodology/approach – The low, medium and high controlled strength blended cement concrete modified with varied proportions of fly and pond ashes were produced. Manufactured sand and recycled plastic coarse aggregate (RPCA) replaced normal fine and coarse aggregates. Concrete samples were tested for workability, mechanical and durability characteristics. Microstructural analysis was performed on cement concrete blended with fly and pond ashes and compared to conventional concrete samples.

Findings – All concrete mixes showed better flowability with values greater than 200 mm. Besides, the maximum flow time was approximately 8 s. The wet density of blended cement concrete-RPCA-based concretes was approximately 30% lower than that of conventional concrete. The compressive strengths of the controlled strength mix at 7 and 28 days were within the specified ranges. While the conventional concrete had slightly higher permeability, the blended cement concrete-RPCA-based concretes had better thermal resistivity and lower thermal conductivity. The scanning electron microscopy analysis revealed the densification of the microstructure due to the filler effects of fly and pond ashes.

Originality/value – This study establishes the prospects of substituting RPCA with normal coarse aggregate in the production of controlled low-strength blended cement concrete, offering benefits of structural fill concrete, lower permeability and thermal conductivity, higher thermal resistivity and reduced density and shrinkage.

Keywords Blended cement concrete, Controlled low-strength concrete, Fly ash, Microstructural analysis, Pond ash, Recycled plastic coarse aggregate

Paper type Research paper

1. Introduction

Plastic has been increasingly used over the past 50 years because of its exceptional functional qualities, affordability and adaptability. Since 1950, the world has produced an astounding 6.3 billion tons of plastic waste, mostly from single-use plastic packaging. Of that waste, 79% ends up in landfills or the environment, endangering marine life, ecosystem and environment (Gündoğdu *et al.*, 2024). The disposal of plastic waste has contributed significantly to environmental conservation because of its extremely low biodegradability and widespread presence. Plastic waste can be chemically or mechanically recycled (Ragaert *et al.*, 2017). The mechanical process is now the most popular way of recycling plastic waste because it allows for the conversion of waste into secondary raw materials or products without seriously altering the material's chemical structure. However, the primary drawbacks of this procedure are the degradation of the mechanical qualities of plastic materials and their inefficiency when handling complicated or layered plastics. In contrast, chemical recycling

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methods such as pyrolysis are promising for recovering waste plastics and can significantly increase recycling rates. The process of pyrolysis is an endothermic procedure that involves heating solid substrates to a temperature of 300°C–900°C in the absence of oxygen to create condensable tars or liquids, solid char (Foong *et al.*, 2020) and gasses that cannot condense (Okuyucu *et al.*, 2022).

Graphene (Jahami *et al.*, 2023), natural fibers (Jahami *et al.*, 2024), steel dust (Jahami *et al.*, 2023) and glass powder (Raydan *et al.*, 2022) have been used as additives and cement substitutes in concrete production, improving the strength and durability performance of concrete. Research has recently revealed that plastic is increasingly studied for potential use in self-compacting and lightweight concrete (Mesbah and Buyle-Bodin, 1999). Replacing coarse aggregates with waste plastic improves the strength of reinforced concrete beams (Jamal *et al.*, 2019). Another study examined the effects of plastic waste (polyethylene terephthalate bottles) as an aggregate on concrete properties (Choi *et al.*, 2005). According to this study, these wastes could reduce concrete's weight by 2.6%–6% and its compressive strength by up to 33% compared to normal concrete. A similar study found decreased compressive strength with increasing plastic content (Batayneh *et al.*, 2007). Compared to regular concrete, the compressive strength decreased by up to 70% when 20% of the sand was replaced by plastic waste. Its application is, therefore, still restricted and more studies are needed. An effective way to lessen the buildup of large volumes of recycled fine aggregates would be to use controlled low-strength materials (CLSMs). Cement, water, fine aggregates and occasionally additional materials or additives are used to create CLSM. It is a low-strength, flowable and self-compacting substance. Instead of traditional compacted fill, CLSM is mainly used for utility bedding, void filling and backfill. Costs can be decreased by minimizing the necessary trench width or excavation size because compaction is unnecessary. During production, materials should be chosen based on cost, availability and intended use (Oyebisi and Alomayri, 2022). The most crucial characteristics are the density and compressive strength in the hardened state, flowability, unit weight, bleeding and setting time in the fresh state. The flowability criteria for CLSM fall between 200 and 300 mm (ASTM D6103, 2017). Water content controls the plastic characteristics of CLSM. Higher flowability is typically the consequence of increased water content, although this can also cause segregation, bleeding and a delay in the hardening process (Nataraja and Nalanda, 2008).

The wet density of standard CLSM varies between 1840 and 2320 kg/m^3 (ACI 229R, 2022; ASTM D6023, 2016). Nevertheless, lower unit weights can be attained by utilizing lightweight aggregates. The amount of bleeding determines the variable setting time. The setup time of CLSM can be calculated by ASTM standards using the resistance of the material to penetration (ASTM C403, 2017). The compressive strength of CLSM at 28 days must be greater than 0.7 MPa (ASTM D4832, 2016), whereas the range for well-compacted soil is 0.3–0.7 MPa. Although CLSM can also be used as a structural filler, its recommended compressive strength for pavement bases, subbases and subgrades should be 1.5 MPa and it should be more than 2 MPa depending on specific needs (ASTM C403, 2017). The cementitious binder material, aggregates and water are the main components of CLSM. The cohesiveness and strength of CLSM are limited by the cement, which is used sparingly. ASTM C 150 states that Portland cement types I and II are widely used (ASTM C150/C150M, 2022). If the initial tests on the combinations yield satisfactory results, other kinds of cement may also be used. Generally, the cement content varies from 30 to 120 kg/m^3 (ASTM D4832, 2016), depending on the strength and setting time requirements. When all other variables remain constant, adding more cement typically increases resistance and a shorter hardening time. Fly ash is an additive that improves strength, decreases permeability, bleeding and shrinkage and improves flowability (Katz and Kovler, 2004).

Compared to normal concrete, CLSM uses more water. For most CLSM mixes comprising aggregates, water levels usually range from 193 to 344 kg/m^3 (Katz and Kovler, 2004). Mixtures with finer particles will have a higher water content. For combinations prepared with Portland cement, the water–cement ratio (w/c) used in various studies varies from 1.00–1.75 (Nataraja and Nalanda, 2008). Class F fly ash and cement-only mixtures can contain up to 590 kg/m^3 of water to attain adequate flowability. This significant variation is mainly caused by the properties of the materials used in CLSM and the required level of flowability. When utilizing highly flowable CLSM, the hydrostatic pressure it exerts is an important factor to consider. When lift fluid pressure is an issue, CLSM can be used; each lift should be given time to solidify before the next is installed. In the CLSM, for example, many lifts may be required to enclose buoyant objects like pipelines or to enclose material with limited strength forms (ACI 229R, 2022).

Generally, fine aggregates are often used in CLSM mixtures as coarse aggregates. The present research used recycled plastic coarse aggregates (RPCA) for CLSM. A semi-mechanized technique was used to generate RPCA from several kinds of plastic waste in four primary forms: high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP) and combined plastic. Cement, fly ash, fine aggregate and water are the usual components of CLSM. Fly ash is a mineral mixture added to the mixture to increase flowability and decrease bleeding (Devaraj *et al.*, 2023). Despite using plastic wastes as aggregate replacement in concrete production, little to no study exists on the application of recycled plastic wastes as aggregates in CLSM modified with PC, fly ash, manufactured sand (M sand) and pond ash. This is the rationale behind this study.

This current research aims to analyze the suitability of RPCA in the production of CLSM. The optimum mix proportion of conventional CLSM made with Portland cement, fly ash, M sand, pond ash, water, natural aggregates and RPCA that achieved the specific fresh and hardened state requirements was established. The effects of RPCA on the workability, mechanical and durability properties of CLSM blended-based cement concrete were investigated. RPCA was used as a total replacement for natural coarse aggregates (NCA). This takes the place of the natural fine aggregate volume, and the results were compared to the conventional CLSM. Depending on the needs, the ideal mixed ratios of CLSM with varying recycled aggregate percentages were established. The findings would establish the prospects of substituting RPCA with normal coarse aggregate in CSLM blended cement concrete, offering benefits such as improved strength and durability.

2. Materials and methods

2.1 Materials

Ordinary Portland cement (OPC) of grade 53, complying with Indian Standards (IS), was used (IS 12269, 2004) as a binder. The cement properties are presented in Table 1.

Fly ash is the most commonly used filler that increases viscosity. Adding fly ash to concrete strengthens the concrete, increases its workability, lessens its permeability, increases density and resists sulfate attacks, reduces alkali-aggregate reaction and lessens efflorescence (Khatib, 2008). Fly ash obtained from Raichur thermal power station, Shaktinagar, Karnataka, India. Pond ash is a byproduct of coal burning in thermal power plants. The pond ash samples were collected for this study at the Raichur Thermal Power Plant in Karnataka, India. Fly and pond ashes were used as OPC substitutes. The properties of fly ash and pond ash are shown in Table 2. Table 2 shows that the fly and pond ashes used exhibit physical properties that satisfy the required specifications.

M sand, or crushed stone sand, was collected from a vertical shaft at a nearby Ramanagaram quarry in Bangalore. The M sand having a maximum particle size of 4.75 mm was used as fine aggregates. Table 3 presents the physical properties of M sand.

NCA is used in the construction industry to make concrete and other building materials. They are generally obtained from different geological formations. These aggregates are typically found in gravel pits or quarries and are composed of naturally occurring rock fragments. Some natural aggregates are gravel, crushed stone, sand, limestone and basalt.

In some construction applications, RPCA is a sustainable substitute for natural coarse aggregates. Plastic waste, such as bottles, containers and packaging, is processed and recycled to create these aggregates. The plastic waste is cleaned, shredded and processed to make granules or tiny particles that can be used as coarse aggregates. In the present work, RPCAs were produced using mechanical recycling, which involves several steps, as shown in Figure 1. After the recycling process is completed, different waste plastic materials in coarse aggregates are obtained independently for each category of HDPE, LDPE, PP and mixed polymers. Figure 2(a)–(c) illustrates the corresponding waste plastic materials. The typical natural aggregates are displayed in Figure 3. Figure 4 shows the particle size distribution of aggregates used. The properties of the aggregates (RPCA and NCA) are shown in Table 4.

2.2 Mixed design proportions

Three mixes of low strength (LS), medium strength (MS) and high strength (HS) were created using CLSM. RPCA and NCA were denoted as an alternate (A) and a conventional (C) for CLSM concrete samples. The mixed proportion was prepared following the report on CLSM (ACI 229R, 2022). The proportions of each raw ingredient are shown in Table 5. From Table 5, fly ash, M sand, RPCA, pond ash, water, OPC 53 and NCA were typically mixed, as shown in Figure 5, to produce CLSM blended concrete samples.

2.3 Experimental testing

2.3.1 Flowability and flow time

The flowability and flow time of the CLSM concrete samples were conducted following the American standard (ASTM D6103, 2017). The flow cylinder was cautiously and swiftly elevated vertically within 5 s of filling and striking off. It was hoisted steadily upward for 2–4 ss, without experiencing any torsional or lateral motion, to a height of at least 15 cm. The entire test took 1.5 min to complete, nonstop, from the beginning of filling to the removal of the flow cylinder. Instantaneously, the spread diameter of the CLSM, as displayed in Figure 6, was measured. Measurements were also taken of the spread diameter's flow time.

2.3.2 Hardening time

Hardening time is the approximate time needed for CLSM to change from a plastic to a hardened state with adequate strength to bear the weight of the material. The hardening time was performed per the procedure highlighted in ASTM standard (ASTM C403, 2017).

2.3.3 Wet density

The wet density of CLSM concrete was determined per ASTM (ASTM D6023, 2016). After that, the wet density was determined by dividing the mass of the sample with its volume.

2.3.4 Compressive strength

Compressive strength tests were performed on specimens with dimensions of 100 × 100 × 100 mm at ages 7 and 28 following IS (IS 516, 2004), using a digital compression testing (2,000 kN) machine until failures occurred. The inner parts of the cube molds were lubricated with oil to remove cubes easily. The molds were filled with fresh concrete and leveled to the top using a trowel. After 24 h, the concrete cubes were removed from the molds, placed in a water tank at 20 ± 5°C and cured for 7 and 28 days. The load was applied steadily on the concrete samples until the specimen failed, noting the maximum load.

Table 1 Properties of the 53-grade OPC

Test	Test method	Results	Specification (IS 12269, 2004)
Specific gravity	(IS 4031-11, 2013)	3.12	3.10–3.15
Standard consistency (%)	(IS 4031-4, 2013)	32	30–35
Initial setting time (min)	(IS 4031-5, 2013)	52	≥30
Final setting time (min)	(IS 4031-5, 2013)	583	≤600
Fineness test (by Blaine air permeability) (m^2/kg)	(IS 4031-2, 2013)	365	370
Compressive strength (MPa)			
7 days	(IS 4031-6, 2024)	37.50	37
28 days		53	53

Source: Table by authors

Table 2 Physical properties of the fly ash and pond ash

Tests	Material	Test method	Result	Specification (IS 3812-1, 2013)
Specific gravity	Fly ash	(IS 1727, 2013)	2.26	2.1–3.0
	Pond ash		2.10	
Fineness test by Blaine air permeability (m^2/kg)	Fly ash	(IS 1727, 2013)	316	320
	Pond ash		315	

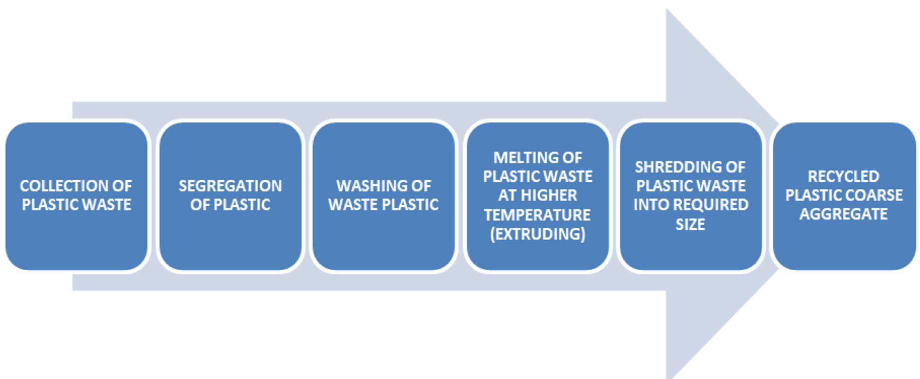
Source: Table by authors

Table 3 Properties of M sand

Test	Test method	Results	Specification (IS 383, 1970)
Specific gravity	(IS 2386-3, 2013)	2.62	2.5–2.9
Bulk density	(IS 2386-3, 2013)	1,747 kg/m^3	Up to 1,750 kg/m^3
Water absorption	(IS 2386-3, 2013)	2.1%	2%–4%
Zone	(IS 2386–1, 2013)	II	I–IV

Source: Table by authors

Figure 1 Process flow chart of the production of recycled plastic aggregates



Source: Figure by authors

Figure 2 Recycled plastic coarse aggregates

Notes: (a) HDPE; (b) PP; (c) LDPE
Source: Figure by authors

2.3.5 Shrinkage
The specimens were prepared according to IS standard (IS 1199–5, 2018), and the gauge stud was assembled. After 28-day curing, specimens were removed from the water, dried with a damp cloth, and aligned and measured the axial rotation for dial gauge readings shown in Figure 7. The measuring was continuous until five consecutive readings were within 0.001 mm of the average, recorded within 2 min. Specimens

Figure 3 Natural coarse aggregates

Source: Figure by authors

were dried in an oven under standard conditions, measured lengths at 27°C ± 2°C, and adjusted for temperature variations. The drying and measurement were continuous until the length stabilized, ensuring consecutive readings differed by less than 0.01 mm after appropriate cooling periods.

2.3.6 Permeability
The term "permeability" of concrete describes the ease with which a fluid can pass through it in the presence of a pressure gradient (through either fractures or permeability). The permeability test followed the IS standard (IS, 3085, 2013). After 28 days, the test specimens were sealed securely with rubber to prevent leaks, and a water pressure of 500 ± 50 kPa was applied for 72 ± 2 h. Afterward, the specimen was removed, and the applied face was wiped. Then, water penetration was measured.

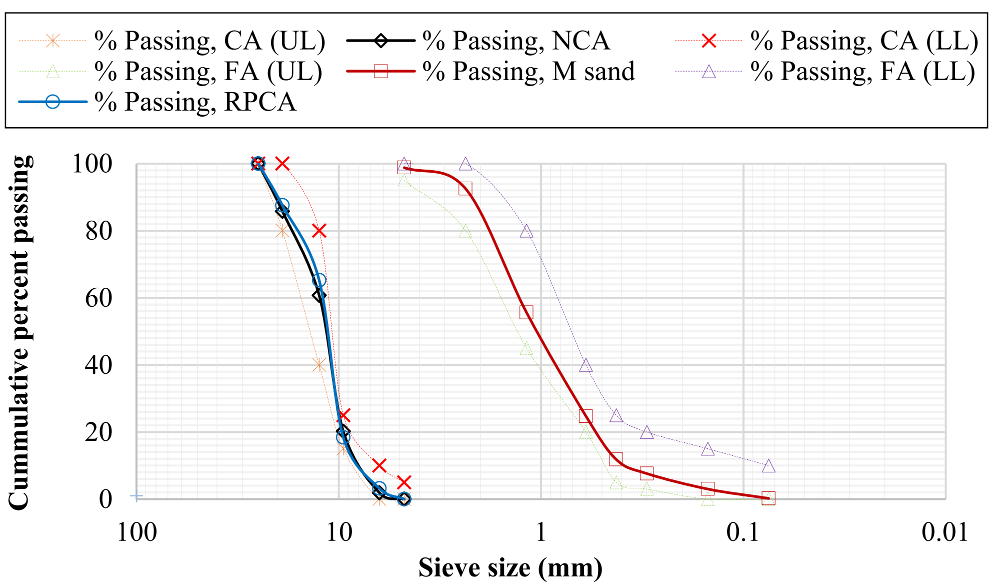
2.3.7 Thermal conductivity and thermal resistivity
The test specimens were prepared following the IS standard (IS 1199–5, 2018). The thermal needle probe was inserted into dense specimens by pushing it into a predrilled hole or directly into loose specimens to match the probe's length. It was ensured that the probe shaft was fully buried without exposure, optionally using thermal grease for better contact. The hole diameter was predrilled to fit the probe snugly. Before use, the probe was calibrated by comparing its conductivity determination against a standard material's known value. The probe's heater wire was connected to a constant current source, applying a known current (e.g., 1.0A) to maintain a temperature change below 10 K in 1,000 s. After cooling, readings, as indicated in Figure 8, were obtained.

2.3.8 Scanning electron microscopy analysis
Further tests were carried out to examine the microstructure of CLSM specimens in terms of workability, mechanical and durability properties. The microstructural characterization involved the analysis of powdered samples with particle sizes of less than 90 microns. The powdered samples were obtained by crushing hardened concrete specimens cured for 28 days. Scanning electron microscopy (SEM) and electron dispersive spectroscopy analyses were performed using the MINI-SEM SNE-3200 M instrument, with a resolution down to 50 μ (Taira *et al.*, 2024).

3. Results and discussion

3.1 Flowability and flow time
The flowability and bleeding rates for fresh samples for various combinations are shown in Figure 9. The use of an appropriate mixture and a sufficient ratio between the aggregate's fine, powder and coarse fractions for high flowability depends upon the w/c ratio. Greater values are achieved by increasing the w/c ratio (Nataraja and Nalanda, 2008). Relevant research maintained that the continuous

Figure 4 Particle size distribution of aggregates used



Notes: CA and FA connote coarse aggregate and fine aggregate; UL and LL represent the upper limit and lower limit
Source: Figure by authors

Table 4 Properties of the aggregates used

Tests	Test method	HDPE plastic	Result obtained (RPCA) LDPE	PP	combined	Result obtained (NCA)	Specification (IS 383, 1970)
Specific gravity	(IS 2386–3, 2013)	1.04	0.93	0.9	1.02	2.61	2.5–3.0
Water absorption (%)	(IS 2386-3, 2013)	0.05	0.04	0	0	0.50	0.1–2.0
Bulk density (kg/m^3)	(IS 2386-3, 2013)	540	340	490	518	1,728	1,200–1,800
Flakiness index (%)	(IS 2386-1, 2013)	11.21	15	10.21	12.42	6.3	10–15
Elongation index (%)	(IS 2386-1, 2013)	18	40	16.9	0	9.4	10–15
Angularity number	(IS 2386-1, 2013)	13.66	33.01	13.19	12.20	–	0–11
Aggregate crushing value (%)	(IS 2386–4, 2013)	2.4	2.3	0	0	24.75	<30 for wearing surfaces (WS) <45 for non-WS
Aggregate impact value (%)	(IS 2386–4, 2013)	2.4	2.3	0	0	26.89	<30 for WS <45 for non-WS
Aggregate abrasive value (%)	(IS 2386–4, 2013)	0	0	0	0	28.60	<30 for WS <50 for non-WS

Source: Table by authors

Table 5 Mixed proportions in kg/m^3

MIX	OPC 53	Fly ash	Pond ash	M sand	RPCA	NCA	Water
LSA	60	120	194.6	83.4	417	–	225
LSC	60	120	194.6	83.4	–	417	225
MSA	90	90	212.4	65.6	417	–	225
MSC	90	90	212.4	65.6	–	417	225
HSA	120	60	194.6	83.4	417	–	225
HSC	120	60	194.6	83.4	–	417	225

Source: Table by authors

Figure 5 Figures showing (a) mixing process, (b) sample preparation and (c) CLSM concrete samples

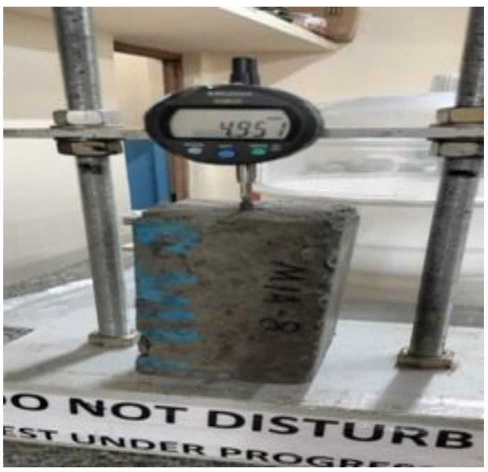
Source: Figure by authors

flowability of CLSM requires a high water content (Yan *et al.*, 2014). As shown in Figure 9(a), the CLSM mixture of LSA (low strength of alternative RPCA) exhibited more remarkable flowability (645 mm) than HSA (630 mm) and LSC (620 mm). Minimum flowability was observed in the MSC, MSA and HSC. When more than 50% of the constituents in the mixture were replaced, the flowability increased because of the decreased absorption of water. For good flowability, the diameter of the spread material should be at least 200 mm (ACI 229R, 2022). Therefore, CLSM concrete made with RPCA can be said to exhibit good flowability. This is consistent with pertinent research that showed excellent properties for flowable backfill and excavatable foundation material in a CLSM mix that included slag and cement kiln dust (Lachemi *et al.*, 2010). As shown in Figure 9(b), the CLSM mixtures of LSA and LSC had minimum flow times of 8 and 9 s compared to MSA, MSC, HSC and HSA with 12, 13, 10 and 14 s. Low deformability and long flow time could be related to high interparticle friction, high CLSM viscosity, or flow obstruction. A flow duration of less than 10 s is required for the materials to self-consolidate for CLSM (Lachemi *et al.*, 2008). As a result, CLSM concrete manufactured with RPCA may self-compact without the need for traditional placement and compacting tools, flow into and fill voids easily and be self-leveling.

Figure 6 Flowability measurement

Source: Figure by authors

Figure 7 Shrinkage test



Source: Figure by authors

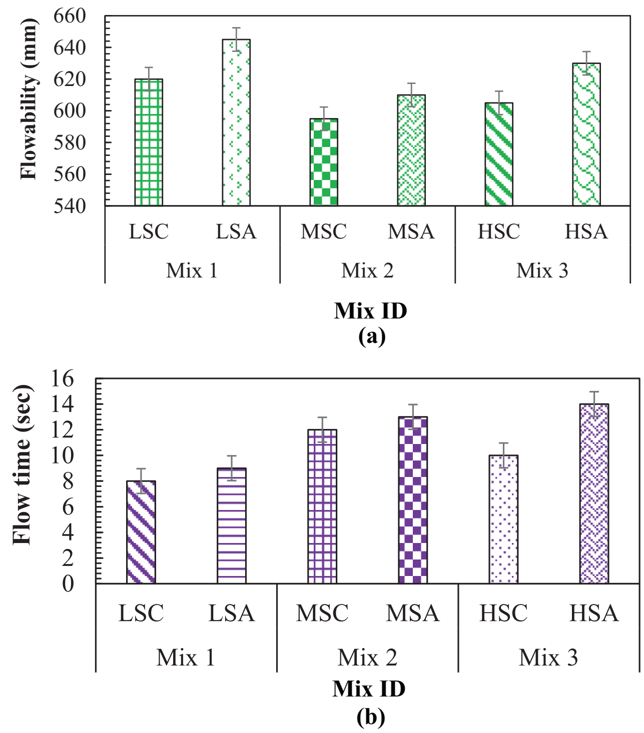
Figure 8 Thermal conductivity and resistivity tests

Source: Figure by authors

3.2 Hardening time

Figure 10 shows that the CLSM mix containing LSA and LSC had longer hardening times, with 35 h and 10 min as initial and about 42 h as final setting times than the other CLSM mixes. There was about 15% and 12% decrease in initial setting times and a 19% and 9% decrease in final setting times of medium and high strengths compared to low-strength material concrete. A related study asserted that a hardening time of 24 h is often suitable (Nataraja and Nalanda, 2008). Under typical circumstances, the hardening process can take as little as 1 h, although it usually takes 3–5 h (ACI 229R, 2022). In most in-situ applications, figuring out the hardening time is challenging (Lachemi *et al.*, 2010). Consequently, the reasons for the variation in these results could be related to the types and proportions of binding materials, permeability and fluidity of CLSM, ambient temperature, humidity and fill depth (ACI 229R, 2022).

Figure 9 Properties of CLSM mixes

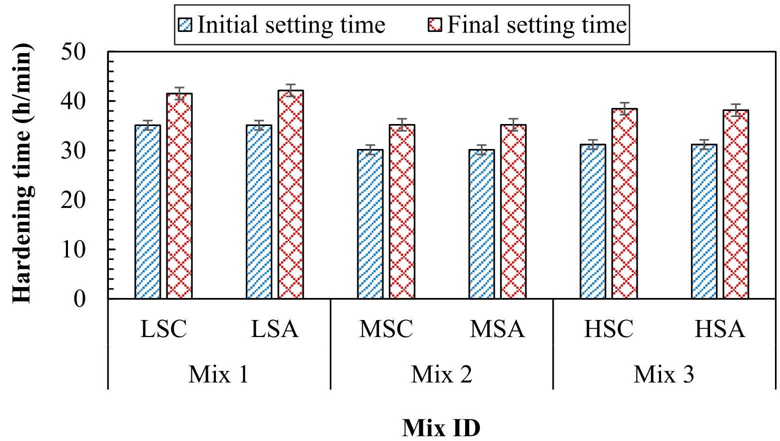


Notes: (a) Flowability; (b) flow times
Source: Figure by authors

3.3 Wet density

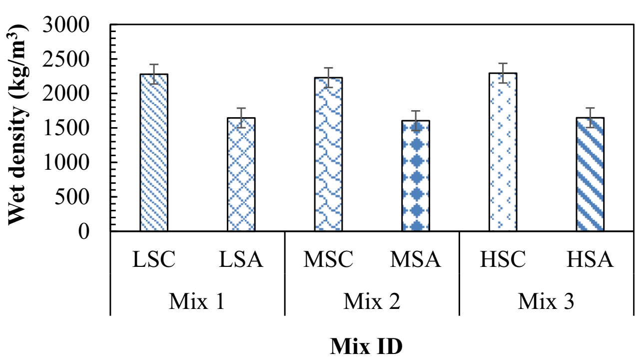
It is evident from Figure 11 that the wet density of CLSM concrete mixes increased with NCA incorporation compared to CLSM concrete mixes modified with RPCA. LSC, MSC and HSC demonstrated higher wet densities of about 2,229 –2,294 kg/m^3 than RPCA with about 1,604–1,647 kg/m^3. These results can be ascribed to the low specific gravity and bulk density of RPCA, which is about 61% and 70% lower than that of NCA (Table 5). A low specific gravity often indicates high porosity, resulting in low density and strength of aggregates (Neville, 1995; Oyebisi *et al.*, 2019). This is evident in Table 4 where the aggregate crushing and impact values of RPCA were nearly zero compared to RPCA with about 25% and 27%. The density of normal CLSM in place is more significant than most compacted materials (ACI 229R, 2022). A CLSM mix with fly ash, cement and water has a density

Figure 10 Hardening time of the CLSM



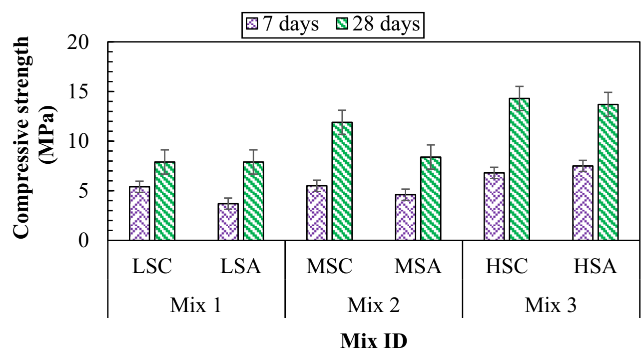
Source: Figure by authors

Figure 11 Wet density of CLSM concrete mixes



Source: Figure by authors

Figure 12 Compressive strength of the CLSM concrete mixes



Source: Figure by authors

between 1,442 and 1,602 kg/m^3. The normal CLSM mix has a density of 1,840–2,320 kg/m^3 and a CLSM mix with pond ash has a density between 1,362 and 1,762 kg/m^3 (ACI 229R, 2022). Comparing these recommendations to the results obtained, it is evident that the CLSM concrete mixes modified with NCA and RPCA were within the stipulated ranges. All applications where conventional CLSM mixtures are being investigated can use low-density CLSM mixtures. The low unit weight is particularly useful in situations where poor soil conditions exist and fill weight needs to be kept to a minimum. Thus, CLSM blended cement concrete modified with RPCA can be used as lightweight concrete, reducing a dead load of structural or mass concrete.

3.4 Compressive strength

Figure 12 displays the compressive strengths of CLSM concrete mixes. At all curing ages, the compressive strength decreased with increasing RPCA content. After seven days, there was about a 32% and 17% decrease in compressive strength when CLSM concrete mixes were incorporated with RPCA for lower and medium strength categories compared to NCA-based CLSM concrete mix. Moreover, approximately 30% and 5% reduction in compressive strength were found in MS- and HS-RPCA-based CLSM concrete mixes compared to NCA-based CLSM concrete mixes. However, there was a 10% increase in compressive strength after seven days with CLSM concrete modified with RPCA compared to NCA-based CLSM concrete for the high strength category. The compressive strength of the CLSM mixture of HSA was 7.50 MPa after seven days, which was the highest of all the CLSM mixtures, as shown in Figure 12. Comparing the CLSM of HSC to other CLSM mixes, Figure 12 shows a maximum compressive strength of 14.3 MPa after 28 days. The compressive strength on day 28 demonstrated the highest possible strength. This could be attributed to the material hydration process producing a lengthy curing phase, which increases the compressive strength (Sheen *et al.*, 2013). Besides, the finer particles of cementitious materials have a void-filling effect that improves the C-A-S-H agent, contributing to the increase in strength (Oyebisi *et al.*, 2020; Oyebisi and Alomayri, 2023). In contrast to a prior study, using cement kiln dust alone was able to produce appropriate CLSM combinations with reasonable fresh and hardened properties; nevertheless, the mixes resulted in reduced strength (Lachemi *et al.*, 2010). Thus, adding slag to cement kiln dust-based CLSM mixtures significantly increases their compressive strength (Lachemi *et al.*, 2010). According to the ACI (ACI 229R, 2022), the lower and upper limits for the 28-day compressive strength of CLSM are 2.1 and 8.3 MPa. This lower limit requirement is necessary to allow for future excavation of CLSM. This material can be used for purposes like structural fill beneath structures where future excavation is improbable due to its top limit of 8.3 MPa (ACI 229R, 2022). Thus, all CLSM mixes produced with RPCA satisfied the ACI recommendations and can be used as structural fill under buildings.

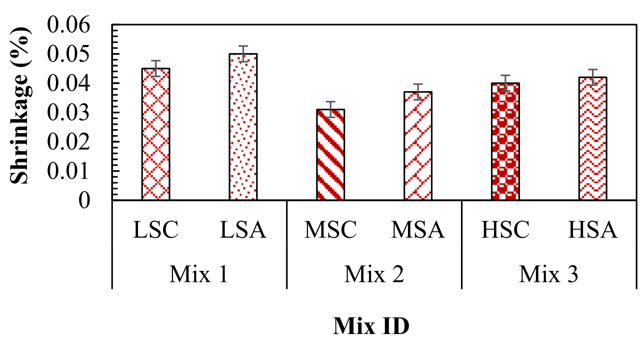
3.5 Shrinkage

As shown in Figure 13, the shrinkage of CLSM concrete mixes marginally increased with RPCA incorporation compared with NCA substitution. There were about 10%, 16% and 5% increases in shrinkage for RPCA-based LS, MS and HS CLSM concrete mixes compared to NCA-based CLSM concrete mixes. The shrinkage of the CLSM mix was maximum at 0.05% for the LSA mix and a minimum of 0.037% for the MSA mix. The increase in shrinkage could be related to the higher volume loss caused by the water content of the RPCA-based CLSM concrete escaping into the surrounding air compared to the NCA-based CLSM concrete mix (Tam *et al.*, 2012). The main factor causing cracks in concrete structures is concrete shrinkage. However, the functionality of CLSM is not impacted by shrinkage or shrinkage cracks (ACI 229R, 2022). Several studies indicated that CLSM shrinks relatively little, with linear shrinkage typically ranging from 0.02% to 0.05% (McLaren and Batsamo, 1986; Naik *et al.*, 1990; Tansley and Bernard, 1981). Ultimately, the shrinkage results obtained in this study align with findings reported by previous studies.

3.6 Permeability

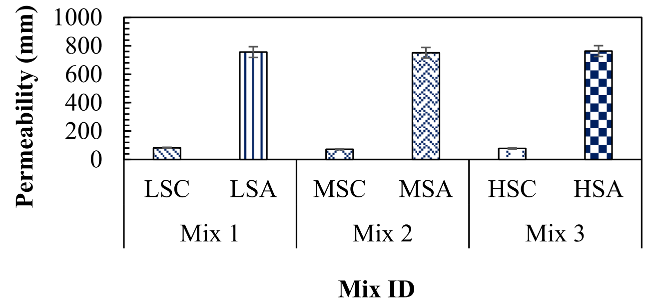
Figure 14 shows a reduction in the permeability of the CLSM concrete mix with RPCA incorporation. Compared to NCA-based CSLM concrete mixes, RPCA-based CLSM concrete mixes showed approximately 17%, 15% and 9% reduced permeability for LS, MS and HS mixes. This reduction can be attributed to a tight network of interconnected pores in the RPCA-based CLSM mix, reducing the concrete water permeability. These results corroborate a previous study that found that the improved microstructure of CLSM mixtures created with wood and coal fly ashes resulted in decreased water permeability (Naik *et al.*, 2004). A more excellent range

Figure 13 Shrinkage of CLSM concrete mixes



Source: Figure by authors

Figure 14 Permeability of CLSM concrete mixes



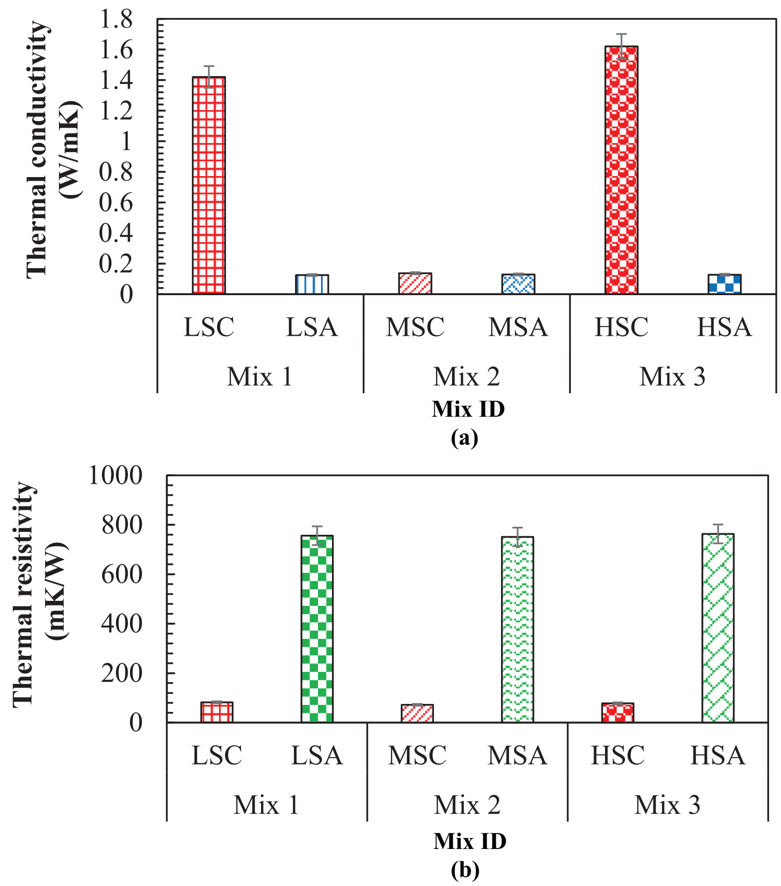
Source: Figure by authors

of permeability of the CLSM mix was suggested by increasing the aggregate or decreasing the cementitious components in the blend (ACI 229R, 2022). Very porous cement paste that envelops the aggregates and discontinuous pores might significantly increase the permeability of concrete (Torres *et al.*, 2015). Permeability increases with a decrease in cementitious components and an increase in aggregate levels, particularly above 80% (Lachemi *et al.*, 2010; McLaren and Batsamo, 1986). Thus, replacing NCA with RPCA in CLSM concrete production results in less permeable concrete.

3.7 Thermal conductivity and thermal resistivity

As indicated in Figure 15(a), the thermal conductivity of CLSM concrete mix reduced with RPCA incorporation. The LSA-CLSM concrete mix demonstrated the lowest thermal conductivity of 0.13 W/mK compared to the HSC-CLSM concrete mix with the highest thermal conductivity of 1.62 W/mK. These resulted in 756 and 78 mK/W thermal resistivity for LSA and HSC in Figure 15(b). From Figure 15(a), LS, MS and HS-RPCA-based CLSM concrete mixes demonstrated a reduction of 91.20%, 5.84% and 92.16% in thermal conductivity compared to LSC, MSC and HSC-NCA-based CLSM concrete mixes. These led to the increase in thermal resistivity, as shown in Figure 15(b), by 89.15%, 90.20% and 87.78% for LS, MS and HS-RPCA-based CLSM concrete mixes compared to LS, MS and HS-NCA-based CLSM concrete mixes. The reduction in thermal conductivity of the RPCA-based CLSM concrete mix can be attributed to its superior flowability, lesser density and minimal shrinkage, making it suitable for application as a thermal grout in geothermal systems as an effective heat transfer medium. Mineral composition, particle size and shape and specific gravity are additional, though less important, elements to take into account (Parmar, 1991, 1992). The thermal resistivity associated with insulation increases as the density decreases. Incorporating air-entrained admixtures or lightweight aggregates or employing foam or cellular mixtures can effectively lower the density of CLSM, thereby enhancing its insulating properties (ACI 229R, 2022). Materials with high density and especially low porosity, which maximize the surface contact area between solid particles, are needed to have high thermal conductivity, such as backfill for subterranean power cables. The thermal conductivity increases with moisture content and dry density (Neville, 1995). Therefore, incorporating normal coarse aggregate with RPCA

Figure 15 Thermal properties of CLSM concrete mixes



Notes: (a) Conductivity; (b) resistivity
Source: Figure by authors

demonstrates a reduction in the thermal conductivity of CLSM-based concrete mix, improving its thermal resistivity.

3.8 Scanning electron microscopy micrographs

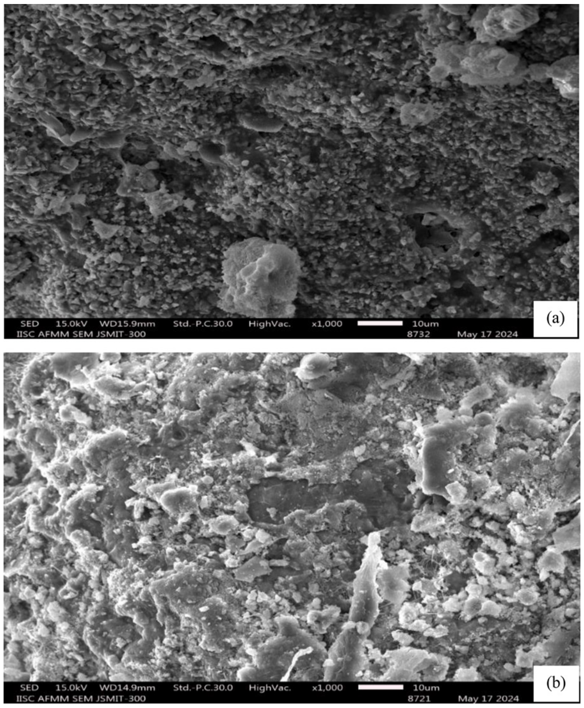
SEM images of the RPCA and NCA-based CLSM mixes revealed significant microstructural characteristics critical for understanding the material properties and potential applications. Figure 16(a) and (b), shows magnifications of 1,000× and a scale of 10 μm with heterogeneous distribution of fly ash and pond ash particles within the concrete matrix. The spherical fly ash particles, which typically range from 1 to 10 μm in diameter, exhibit a smooth surface texture, indicating their formation process through rapidly cooling molten ash. In contrast, the pond ash particles display irregular, angular shapes and a rougher surface, suggesting a different genesis involving slower cooling and partial weathering. The interfacial zones between the ash particles and the cementitious matrix are discernible, highlighting the degree of bonding and potential voids that could influence the mechanical properties of the composite material. The fly ash particles contained in the matrix can be seen to be partially or completely reacted, indicating areas of potential pozzolanic activity that could contribute to the long-term strength and durability of the concrete. Furthermore, the image provides evidence of the densification of the microstructure due to the filler effect and the pozzolanic reaction of the ashes, which contributes to the overall performance enhancement of the concrete mix.

4. Conclusions

This work examined the properties of controlled low-strength blended cement concrete using recycled plastic waste and M sand as coarse aggregate and fine aggregate replacements. These deductions are made in light of the findings:

- All mixes exhibited excellent flowability, with flows exceeding 200 mm and maximum flow times of approximately 8 seconds.
- The wet density of the RPCA-based CLSM mix was approximately 30% lower than that of the NCA-based CLSM mix, which was attributed to the presence of RPCA.
- The 7 and 28 days of compressive strength of RPCA-based CLSM concrete mixes were within the specified ranges.
- Shrinkage met the specifications for all CLSM concrete mixes except for LSA, which showed marginally higher values.

Figure 16 SEM micrographs for (a) RPCA-based mix and (b) NCA-based mix



Source: Figure by authors

- RPCA-based CLSM concrete mixes showed a 9%–17% lower permeability than NCA-based CLSM concrete mixes.
- RPCA-based CLSM concrete mix demonstrated approximately 92% lesser thermal conductivity, resulting in a 90% increase in thermal resistivity compared to NCA-based CLSM concrete mix.

The study concluded that RPCA, when used in alternate concrete mixes, can effectively serve CLSM applications, such as structural fill under buildings, backfilling and areas requiring lower thermal conductivity, higher thermal resistivity and reduced shrinkage. Proper mixing and optimized utilization of industrial byproducts can effectively fulfill the requirements of CLSM.

This research demonstrated promising results based on short-term performance (7 and 28 days). However, future studies can investigate the long-term mechanical and durability properties of controlled low-strength blended cement concrete using recycled plastic waste and M sand as coarse aggregate and fine aggregate substitutes.

References

ACI 229R (2022), *Report on Controlled Low-Strength Materials*, Farmington Hills, MI.

ASTM C150/C150M (2022), *Standard Specification for Portland Cement*, West, Conshohocken, USA.

ASTM C403 (2017), *Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance*, West Conshohocken, PA, USA.

ASTM D4832 (2016), *Standard Test Method for Preparation and Testing of Controlled Low Strength Material (CLSM) Test Cylinders*, West Conshohocken, PA, USA.

ASTM D6023 (2016), "Standard test method for density (unit weight)", *Yield, Cement Content, and Air Content (Gravimetric) of Controlled Low-Strength Material (CLSM), West*, Conshohocken, PA, USA.

ASTM D6103 (2017), *StandardTest Method for Flow Consistency of Controlled Low Strength Material (CLSM)*, West Conshohocken, United States.

Batayneh, M., Marie, I. and Asi, I. (2007), "Use of selected waste materials in concrete mixes", *Waste Management*, Vol. 27 No. 12, pp. 1870-1876, doi: 10.1016/j.wasman.2006.07.026.

Choi, Y.W., Moon, D.J., Chung, J.S. and Cho, S.K. (2005), "Effects of waste PET bottles aggregate on the properties of concrete", *Cement and Concrete Research*, Vol. 35 No. 4, pp. 776-781, doi: 10.1016/j.cemconres.2004.05.014.

Devaraj, V., Mangottiri, V. and Balu, S. (2023), "Prospects of sustainable geotechnical applications of manufactured sand slurry as controlled low strength material", *Construction and Building Materials*, Vol. 400, doi: 10.1016/j.conbuildmat.2023.132747.

Foong, S.Y., Liew, R.K., Yang, Y., Cheng, Y.W., Yek, P.N.Y., Wan Mahari, W.A., Lee, X.Y., *et al.* (2020), "Valorization of biomass waste to engineered activated biochar by microwave pyrolysis: progress, challenges, and future directions", *Chemical Engineering Journal*, Vol. 389, doi: 10.1016/j.cej.2020.124401.

Gündoğdu, S., Bour, A., Köşker, A.R., Walther, B.A., Napierska, D., Mihai, F.-C., Syberg, K., *et al.* (2024), "Review of microplastics and chemical risk posed by plastic packaging on the marine environment to inform the global plastics treaty", *Science of The Total Environment*, Vol. 946, p. 174000, doi: 10.1016/j.scitotenv.2024.174000.

IS 1199-5 (2018), *Fresh Concrete - Methods of Sampling, Testing and Analysis Part 5 Making and Curing of Test Specimens*, New Delhi.

IS 12269 (2004), *Specification for 53 Ordinary Portland Cement*, New Delhi.

IS 1727 (2013), *Methods of Test for Pozzolanic Materials*, New Delhi.

IS 2386-1 (2013), *Methods of Test for Aggregates for Concrete, Part I: Particle Size and Shape*, New Delhi.

IS 2386-3 (2013), *Methods of Test for Aggregates for Concrete, Part 3: Specific Gravity, Density, Voids, Absorption and Bulking*, New Delhi.

IS 2386-4 (2013), *Methods of Test for Aggregates for Concrete, Part 4: Mechanical Properties*, New Delhi.

IS 3085 (2013), *Method of Test for Permeability of Cement Mortar and Concrete*, New Delhi.

IS 3812-1 (2013), *Pulverized Fuel Ash - Specification Part 1 for Use as a Pozzolana in Cement, Mortar, and Concrete*, New Delhi.

IS 383 (1970), *Specification for Coarse and Fine Aggregates From Natural Sources For Concrete*, New Delhi.

IS 4031-11 (2013), *Methods of Physical Tests for Hydraulic Cement, Part 11: Determination of Density*, New Delhi.

IS 4031-2 (2013), *Methods of Physical Tests for Hydraulic Cement, Part 2: Determination of Fineness by Specific Surface by Blaine Air Permeability Method*, New Delhi.

IS 4031-4 (2013), *Methods of Physical Tests for Hydraulic Cement, Part 4: Determination of Consistency of Standard Cement Paste*, New Delhi.

IS 4031-5 (2013), *Methods of Physical Tests For Hydraulic Cement, Part 5 - Determination of Initial and Final Setting Times*, New Delhi.

IS 4031-6 (2024), *Methods of Physical Tests for Hydraulic Cement: Part 6 Determination of Compressive Strength of Hydraulic Cement Other than Masonry Cement (First Revision)*, New Delhi.

IS 516 (2004), *Methods of Test for Strength of Concrete*, New Delhi.

Jahami, A., Mouzanar, H., Mahfouz, S., Khatib, J. and Sonebi, M. (2023), "Effect of graphene as additive on the mechanical properties of concrete", *NanoWorld Journal*, Vol. 9, doi: 10.17756/nwj.2023-s2-015.

Jahami, A., Younes, H. and Khatib, J. (2023), "Enhancing reinforced concrete beams: investigating steel dust as a cement substitute", *Infrastructures*, Vol. 8 No. 11, p. 157, doi: 10.3390/infrastructures8110157.

Jahami, A., Zeaiter, N. and Cheaib, M. (2024), "Reviewing the potential: a comprehensive review of natural fibers (NFs) in structural concrete and their multifaceted influences", *Innovative Infrastructure Solutions*, Vol. 9 No. 4, p. 102, doi: 10.1007/s41062-024-01384-x.

Jamal, K., Ali, J., Adel, E. and Oussama, B. (2019), "Structural performance of reinforced concrete beams containing plastic waste caps", *Magazine of Civil Engineering*, Vol. 91 No. 7, pp. 73-79.

Katz, A. and Kovler, K. (2004), "Utilization of industrial by-products for the production of controlled low strength materials (CLSM)", *Waste Management*, Vol. 24 No. 5, pp. 501-512, doi: 10.1016/S0956-053X(03)00134-X.

Khatib, J.M. (2008), "Performance of self-compacting concrete containing fly ash", *Construction and Building Materials*, Vol. 22 No. 9, pp. 1963-1971, doi: 10.1016/j.conbuildmat.2007.07.011.

Lachemi, M., Hossain, K.M.A., Shehata, M. and Thaha, W. (2008), "Controlled low strength materials incorporating cement kiln dust from various sources", *Cement and Concrete Composites*, Vol. 30 No. 5, pp. 381-392, doi: 10.1016/j.cemconcomp.2007.12.002.

Lachemi, M., Şahmaran, M., Hossain, K.M.A., Lotfy, A. and Shehata, M. (2010), "Properties of controlled low-strength materials incorporating cement kiln dust and slag", *Cement and Concrete Composites*, Vol. 32 No. 8, pp. 623-629, doi: 10.1016/j.cemconcomp.2010.07.011.

McLaren, R. and Batsamo, N. (1986), "Fly ash design manual for road and site application; volume 2: Slurried placement".

Mesbah, H.A. and Buyle-Bodin, F. (1999), "Efficiency of polypropylene and metallic fibres on control of shrinkage and cracking of recycled aggregate mortars", *Construction and Building Materials*, Vol. 13 No. 8.

Naik, T., Kraus, R., Siddique, R. and Chun, Y.-M. (2004), "Properties of controlled low-strength materials made with wood fly ash", *Journal of ASTM International*, Vol. 1 No. 6, pp. 1-10, doi: 10.1520/JAI11871.

Naik, T., Ramme, B.W. and Kolbeck, H.J. (1990), *Filling Abandoned Underground Facilities with CLSM Fly Ash Slurry, ACI Concrete International.*

Nataraja, M.C. and Nalanda, Y. (2008), "Performance of industrial by-products in controlled low-strength materials (CLSM)", *Waste Management*, Vol. 28 No. 7, pp. 1168-1181, doi: 10.1016/j.wasman.2007.03.030.

Neville, A.M. (1995), *Properties of Concrete*, 4th ed., Longman, Harlow, U.K.

Okuyucu, O., Jayawickrama, P. and Senadheera, S. (2022), "The relationship between curing regime and mechanical properties of controlled low-strength material", *Construction and Building Materials*, Vol. 315, doi: 10.1016/j.conbuildmat.2021.125460.

Oyebisi, S. and Alomayri, T. (2022), "Cement-based concrete modified with Vitellaria Paradoxa ash: a lifecycle assessment", *Construction and Building Materials*, Vol. 342, doi: 10.1016/j.conbuildmat.2022.127906.

Oyebisi, S. and Alomayri, T. (2023), "Artificial intelligence-based prediction of strengths of slag-ash-based geopolymer concrete using deep neural networks", *Construction and Building Materials*, Vol. 400, p. 132606, doi: 10.1016/j.conbuildmat.2023.132606.

Oyebisi, S., Igba, T. and Oniyide, D. (2019), "Performance evaluation of cashew nutshell ash as a binder in concrete production", *Case Studies in Construction Materials*, Vol. 11, doi: 10.1016/j.cscm.2019.e00293.

Oyebisi, S., Igba, T., Raheem, A. and Olutoge, F. (2020), "Predicting the splitting tensile strength of concrete incorporating anacardium occidentale nut shell ash using reactivity index concepts and mix design proportions", *Case Studies in Construction Materials*, Vol. 13, doi: 10.1016/j.cscm.2020.e00393.

Parmar, D. (1991), *Current Practices for Underground Cable Thermal Backfill*, Montreal, Canada.

Parmar, D. (1992), *Optimizing the Use of Controlled Backfill to Achieve High Ampacities on Transmission Cable*, Montreal, Canada.

Ragaert, K., Delva, L. and Van Geem, K. (2017), "Mechanical and chemical recycling of solid plastic waste", *Waste Management*, Vol. 69, doi: 10.1016/j.wasman.2017.07.044.

Raydan, R., Khatib, J., Jahami, A., El Hamoui, A.K. and Chamseddine, F. (2022), "Prediction of the mechanical strength of concrete containing glass powder as partial cement replacement material", *Innovative Infrastructure Solutions*, Vol. 7 No. 5, p. 311, doi: 10.1007/s41062-022-00896-8.

Sheen, Y.N., Zhang, L.H. and Le, D.H. (2013), "Engineering properties of soil-based controlled low-strength materials as slag partially substitutes to Portland cement", *Construction and Building Materials*, Vol. 48, pp. 822-829, doi: 10.1016/j.conbuildmat.2013.07.046.

Taira, K., Webster, N.A.S., Ignácio, I.R., Ware, N., D'Angelo, A.M., Zhang, L. and Pownceby, M.I. (2024), "Valorisation potential of low-grade fly ash as a sustainable MgO source for iron ore sintering: insights from in situ X-ray diffraction and tablet studies", *Journal of Environmental Chemical Engineering*, Vol. 12 No. 3, doi: 10.1016/j.jece.2024.112934.

Tam, C.M., Tam, V.W.Y. and Ng, K.M. (2012), "Assessing drying shrinkage and water permeability of reactive powder

concrete produced in Hong Kong", *Construction and Building Materials*, Vol. 26 No. 1, pp. 79-89, doi: 10.1016/j.conbuildmat.2011.05.006.
Tansley, R. and Bernard, R. (1981), *Specification for Lean Mix Backfill*, USA.
Torres, A., Hu, J. and Ramos, A. (2015), "The effect of the cementitious paste thickness on the performance of pervious concrete", *Construction and Building Materials*, Vol. 95, pp. 850-859, doi: 10.1016/j.conbuildmat.2015.07.187.
Yan, D.Y.S., Tang, I.Y. and Lo, I.M.C. (2014), "Development of controlled low-strength material derived from beneficial reuse of bottom ash and sediment for green construction", *Construction and Building Materials*, Vol. 64, pp. 201-207, doi: 10.1016/j.conbuildmat.2014.04.087.

Further reading

Rossignolo, J.A. and Agnesini, M.V.C. (2004), "Durability of polymer-modified lightweight aggregate concrete", *Cement and Concrete Composites*, Vol. 26 No. 4, pp. 375-380, doi: 10.1016/S0958-9465(03)00022-2.
Siddique, R., Khatib, J. and Kaur, I. (2008), "Use of recycled plastic in concrete: a review", *Waste Management*, Vol. 28 No. 10, pp. 1835-1852, doi: 10.1016/j.wasman.2007.09.011.
Sikalidis, C.A., Zabaniotou, A.A. and Famellos, S.P. (2002), *Utilisation of Municipal Solid Wastes for Mortar Production*, Vol. 36

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