

Chloride and Carbonation Resistance of Calcined Clay and Metakaolin Concretes: Systematic Review, Meta-Analysis and Indian Service-Life Implications

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Abstract

Limestone calcined clay cements are now standardized in India, but durability design under IS 456 remains prescriptive, and quantitative evidence on chloride transport and carbonation is fragmented. This study combined a PRISMA 2020 systematic review of open-access literature (1800 records, 2010–2026) with a random-effects meta-analysis of log response ratios between calcined clay or metakaolin mixes and same-study Portland cement controls, and with a meta-regression on clay kaolinite content. Twenty-five studies were synthesized. Calcined clay and metakaolin binders reduced the chloride migration coefficient (response ratio 0.40, 95% CI 0.29–0.55; 12 studies), the charge passed (0.36, 0.23–0.56; 12 studies) and the apparent diffusion coefficient (0.28, 0.13–0.61; 5 studies), but approximately doubled the accelerated carbonation depth (2.09, 1.43–3.07; 5 studies; exploratory). Heterogeneity was very high, prediction intervals included unity, and calcined clay and metakaolin did not differ. Each 10-percentage-point increase in kaolinite content multiplied the chloride response ratio by 0.70 (0.59–0.84). In an illustrative mean-value calculation with the fib Bulletin 34 chloride model and identical ageing assumptions, the pooled migration ratio reduced the cover needed against chloride-induced depassivation by more than one third. Kaolinite-rich calcined clay binders therefore offer a consistent chloride advantage, whereas carbonation requires explicit cover or curing provisions. Performance-based Indian specifications should require mix-specific migration and carbonation testing.

Keywords

calcined clay, metakaolin, chloride migration, carbonation, meta-analysis

1 Introduction

1.1 Low-clinker binders and the Indian context

Reducing the clinker factor of cement is one of the few measures that can lower the CO₂ intensity of concrete at the scale required, and calcined kaolinitic clays are the only supplementary cementitious material (SCM) available in sufficient quantity to support it globally. Combining calcined clay with limestone exploits a synergy between the pozzolanic reaction of metakaolin and the formation of carboaluminate phases, which allows clinker replacement levels of about 50% while maintaining early strength [1]. This principle underlies limestone calcined clay cement (LC3) [2]. The reactivity of the calcined clay is governed mainly by its kaolinite content, which can be assessed with rapid tests such as the R3 method [3].

India has moved early towards implementation. Concretes made with LC3 from Indian raw materials have been characterized for mechanical and durability performance [4], and service-life and life-cycle analyses of reinforced concrete with LC3 have been reported [5]. The Bureau of Indian Standards has since published a product standard for Portland calcined clay limestone cement, IS

18189:2023 [6]. Durability design in India, however, still follows the prescriptive approach of IS 456:2000 [7]. Exposure classes from mild to extreme are linked to minimum cement content, maximum water–cement ratio, minimum grade and nominal cover, without explicit reference to binder type or to measured transport properties. Indian clays also vary widely in kaolinite content, so a single prescriptive rule may be conservative for some LC3-type concretes and unconservative for others.

1.2 The durability trade-off

Calcined clay binders affect the two main causes of reinforcement corrosion in opposite directions. Pore refinement and the binding of chlorides by aluminate hydrates generally reduce chloride transport, as summarized by RILEM TC 282-CCL [8]. Lower clinker content, however, reduces the portlandite buffer available to consume CO₂, which tends to increase the rate of carbonation, as reviewed by RILEM TC 281-CCC for SCM concretes in general [9]. Corrosion of steel in carbonated concrete depends further on moisture conditions, which makes the practical consequences of faster carbonation exposure-dependent [10]. Individual studies on LC3-type

concretes have examined carbonation [11] and the chloride resistance of binders made with low-grade clays [12]. Both effects therefore need to be quantified before calcined clay concretes can be specified with confidence.

1.3 Existing reviews and the knowledge gap

The RILEM technical committee reviews [8–10] are authoritative state-of-the-art reports, but they are qualitative. They do not provide pooled effect sizes with confidence intervals, they do not quantify between-study heterogeneity, and they do not link the magnitude of the effect to design inputs such as the chloride migration coefficient used in the fib Bulletin 34 service-life model [13]. Published data are also difficult to combine because test methods differ (non-steady-state migration, rapid chloride permeability, bulk diffusion and accelerated or natural carbonation) and because most studies report durability results only in graphs.

1.4 Objectives

This study combines a systematic review with a meta-analysis of paired comparisons between calcined clay (CC) or metakaolin (MK) mixes and Portland cement (PC) controls tested in the same study. It addresses three research questions. RQ1: by how much do CC and MK binders change chloride transport indicators and carbonation depth relative to PC? RQ2: does the kaolinite content of the clay explain part of the variation between studies, and do LC3-type calcined clays differ from high-purity MK? RQ3: what does the pooled effect imply, illustratively, for the cover required against chloride-induced depassivation in the IS 456 exposure classes? The review is designed as a transparent, reproducible evidence base. All data, assumptions and limitations are reported, so that the estimates can be updated as more studies become available.

2 Materials and methods

2.1 Protocol and reporting

The review followed the PRISMA 2020 reporting guideline [14]. The protocol (eligibility criteria, outcomes, effect-size metric and planned moderators) was fixed before data extraction began. The review protocol was not registered. The search, screening and extraction were carried out in four documented phases, and every decision is logged in the supplementary dataset (Section 2.12).

2.2 Information sources and search

Two bibliographic sources were searched for records published between 2010 and 2026. OpenAlex was searched in titles and abstracts with the Boolean string ("calcined

clay" OR LC3 OR "limestone calcined clay" OR metakaolin) AND (concrete OR mortar) AND (chloride OR "migration coefficient" OR diffusion OR resistivity OR carbonation), which returned 1362 records. Crossref was queried with six relevance-ranked queries combining LC3 or calcined clay with chloride, carbonation, migration or resistivity terms (top 150 per query), which returned 438 unique DOIs. Semantic Scholar and CORE could not be used because of rate limiting. Open-access status was taken from OpenAlex. Scopus and Web of Science were not searched, and only open-access full texts were retrieved. This restriction is discussed in Section 5.5.

2.3 Eligibility criteria

Studies were eligible if they (i) tested concrete or mortar (paste-only studies were excluded); (ii) contained at least one mix in which calcined clay, LC3 or metakaolin replaced part of the cement; (iii) included a Portland cement control tested in the same study under the same protocol; and (iv) reported at least one target outcome quantitatively in a table, the text or a readable figure. The target outcomes were the non-steady-state chloride migration coefficient D_{nssm} (NT BUILD 492 or equivalent rapid chloride migration) [15]; the charge passed in the rapid chloride permeability test (RCPT, ASTM C1202) [16]; the apparent chloride diffusion coefficient D_a from bulk diffusion or ponding (e.g. ASTM C1556) [17]; accelerated carbonation depth or coefficient (e.g. EN 12390-12) [18]; natural carbonation; and electrical resistivity. Alkali-activated and geopolymer binders, reviews, modelling-only studies, non-English papers and studies in which the reference mix itself contained another SCM (for example fly ash, slag or silica fume) were excluded. Studies with a Portland-limestone or general-purpose cement control were retained but flagged. Studies in which the CC or MK was combined with a second SCM in a ternary blend were excluded.

2.4 Screening and retrieval

After removal of 68 duplicates, 1732 records were screened on title and abstract. Screening used a rule-based first pass on keywords followed by a manual second pass. Metakaolin-only records (472) were initially deferred and later screened against the same criteria, so that MK could serve as the high-purity end of the kaolinite range. Because the rule-based pass could not judge records without an abstract, two records flagged during drafting as clearly on-topic (Dhandapani et al. [4] and Zolfagharnasab et al. [12]) were re-screened by hand, found eligible at title level and moved to full-text retrieval. Full texts were therefore sought

for 426 records (156 CC/LC3 and 270 MK). Retrieval was restricted to legal open-access copies (publisher sites, Europe PMC and PMC, institutional repositories and author-posted manuscripts). Records without an open-access copy were not retrieved, and no authors were contacted.

2.5 Data extraction and digitization

For each eligible comparison the following were extracted: binder composition (clinker, calcined clay and limestone fractions), the kaolinite content of the clay as reported, material type (concrete, self-compacting concrete, high-strength concrete or mortar), water-to-binder ratio (w/b), curing, test age, test method, the outcome value of the CC/MK mix and of the PC control, any reported dispersion (SD or error bar) and the number of replicates. Every extracted value carries a page, table or figure reference and an uncertainty flag. Values were taken preferentially from tables or text. Where data were available only in graphs, they were digitized in two independent runs with separate axis calibrations, and the mean of the two runs was used. The reading error was recorded, and digitized values were checked against any value quoted in the text (for example, a reference value given in the text, printed percentage labels, or a percentage reduction stated in the abstract). Printed data labels were read directly where available. The extraction dataset contains 256 rows and the digitization log 118 readings. The analysis file contains 106 CC/MK-versus-PC comparisons, including those from sensitivity-only studies.

The kaolinite content was coded as reported by each study. Definitions differed: some studies reported the kaolinite content of the raw clay, others the calcined kaolinite content, and others the metakaolinite content of the calcined clay. MK studies were coded as a separate subgroup and were not assigned a numerical kaolinite value.

2.6 Effect size

The effect size was the natural logarithm of the response ratio [19],

$$\ln RR = \ln \left(\frac{X_{CC}}{X_{PC}} \right) \quad (1)$$

where X is the mean outcome of the CC/MK mix and of the same-study PC control. $RR < 1$ indicates lower chloride transport (beneficial), and $RR > 1$ for carbonation indicates a faster carbonation front (detrimental). The sampling variance was approximated by the delta method [19],

$$v = \frac{CV_{CC}^2}{n_{CC}} + \frac{CV_{PC}^2}{n_{PC}} \quad (2)$$

Most studies did not report SDs or replicate numbers. The primary analysis therefore imputed the coefficient of variation (CV) from test-method precision data and assumed $n = 3$ specimens per arm. The imputed CVs were 13% for Dnssm (the reproducibility coefficient of variation for Portland cement and silica fume concrete in the precision section of NT BUILD 492; the repeatability CV is 9%) [15]; 12.3% for RCPT (the single-operator CV in the precision statement of ASTM C1202-22e1; the multilaboratory CV is 18.0%) [16]; 13% for Da (assumed; no standard value was verified); and 15% for accelerated carbonation (assumed; no verified precision value). When several CC/MK mixes in a study shared one control, their $\ln RR$ values were averaged and the variance was computed as $v = \Sigma v_t/k^2 + v_c$, which accounts for the shared control. When a study contained several controls, the control-specific estimates were averaged. Each study therefore contributed one effect size per outcome. A sensitivity analysis replaced the imputed CVs with the SDs reported in, or digitized from, the original studies where these were available.

2.7 Statistical synthesis

Study-level $\ln RR$ values were pooled per outcome with a random-effects model. The between-study variance τ^2 was estimated by restricted maximum likelihood (REML), with the DerSimonian–Laird estimator as a check. Results are reported as $RR = \exp(\ln RR)$ with 95% confidence intervals (CI). Heterogeneity was quantified with Cochran's Q , I^2 and τ^2 , and 95% prediction intervals (PI) were computed with a t -distribution on $k - 2$ degrees of freedom. Subgroup differences between CC and MK were tested with a z -test on the difference of subgroup means. Pooling was performed only for outcomes with at least five independent studies. Natural carbonation and electrical resistivity did not reach this threshold and were synthesized narratively.

2.8 Sensitivity analyses

Pre-specified sensitivity analyses were: (i) use of reported or digitized SDs instead of imputed CVs; (ii) exclusion of studies from low-credibility venues, of approximate values and of comparisons with an unclear test age; (iii) leave-one-out analysis; and (iv) outcome-specific checks. The outcome-specific checks were exclusion of a study whose control value differed between figure and text (RCPT), exclusion of calcareous-clay mixes (RCPT),

exclusion of values derived from reported percentage changes (Dnssm), and addition of two studies in which Da was fitted to profiles obtained after an accelerated migration test (Da).

2.9 Kaolinite meta-regression

The effect of kaolinite content was explored at the comparison level, using all CC comparisons with a reported kaolinite value across the three chloride outcomes. Model A regressed lnRR on kaolinite content (per 10 percentage points, pp) with outcome indicator variables. Cluster-robust (CR1) standard errors by study and t-based intervals with G – 1 degrees of freedom were used, where G is the number of studies. Model B used only studies containing more than one kaolinite level and included study-by-outcome fixed effects, so that the slope is estimated within studies and is not confounded by between-study differences. Both models are exploratory because the number of clusters is small.

2.10 Credibility appraisal

A formal risk-of-bias tool for materials-testing studies is not established. Each study was therefore appraised on reporting items: control type, stated test age, reporting of dispersion and replicates, internal consistency between text, tables and figures, and venue. Three studies were published in venues considered to have low editorial credibility. They are marked † in the tables and figures and were excluded in sensitivity analysis (ii).

2.11 Illustrative service-life model

The pooled Dnssm ratio was translated into required cover using the chloride ingress model of fib Bulletin 34 [13]. The chloride content at depth x and time t is

$$C(x, t) = C_0 + (C_s - C_0) \cdot \left[1 - \operatorname{erf} \left(\frac{x - \Delta x}{2 \sqrt{D_{app}(t) \cdot t}} \right) \right] \quad (3)$$

$$D_{app}(t) = k_e \cdot D_{RCM,0} \cdot k_t \cdot \left(\frac{t_0}{t} \right)^a \quad (4)$$

$$k_e = \exp \left[b_e \left(\frac{1}{T_{ref}} - \frac{1}{T_{real}} \right) \right] \quad (5)$$

where Cs is the surface chloride content, Δx the depth of the convection zone, DRCM,0 the migration coefficient at the reference age t0 = 28 d, a the ageing exponent, kt a transfer parameter (kt = 1) and ke the temperature factor, in which be is a regression variable, Tref the reference temperature and Treall the temperature of the structural element or ambient air. Setting C(x,t) equal to the critical

chloride content Ccrit and solving for x gives, with C0 = 0, the cover at which depassivation occurs at the end of the design life:

$$x_{req} = \Delta x + 2 \sqrt{D_{app}(t) \cdot t} \cdot \operatorname{erf}^{-1} \left(1 - \frac{C_{crit}}{C_s} \right) \quad (6)$$

The calculation was run with mean values only, as a deterministic illustration and not as a reliability-based design. All inputs and their sources are listed in Section 4.1. DRCM,0 for PC concrete was taken as the median of the 28-day CEM I concrete controls with w/b 0.40–0.50 in six included studies, one value per study [4,20–24]. DRCM,0 for CC/MK concrete was obtained by multiplying the PC value by the pooled RR, its confidence limits and the upper prediction limit. The same ageing exponent was used for both binders in the base case. This is conservative for CC/MK if blended binders age faster, but no LC3-specific value was found in the included studies. A higher exponent was examined for CC/MK as a hypothetical sensitivity case. The surface chloride contents assigned to the IS 456 exposure classes are assumed scenario values, not measured data, and are labelled as such.

2.12 Software and data

All calculations were performed in Python (NumPy, SciPy, Matplotlib), and the scripts used to build the analysis dataset, run the meta-analysis and meta-regression, and produce every figure and table are provided as supplementary material.

3 Results

3.1 Study selection

The selection process is shown in Fig. S1 in the Supplementary material. Of the 1800 records identified, 68 duplicates were removed and 1732 were screened, of which 1306 were excluded. Full texts were sought for 426 reports. Of these, 130 were obtained and 296 could not be retrieved: 152 were closed access with no open-access copy (including Zolfagharnasab et al. [12]), and 144 had an open-access copy that could not be downloaded automatically and await manual retrieval. The counts were reconciled against the full-text files on disk: two records that had been listed for manual download were already held as full text, and the earlier running total of retrieved reports had been undercounted by four. Among the 130 assessed full texts, 22 were excluded with reasons (for example, no PC-only control, a reference containing another SCM, no eligible outcome, a review, or a non-comparable test), 6 contributed narrative evidence only, and 75 were still awaiting full

assessment or digitization at the time of analysis. Twenty-five studies entered the quantitative synthesis, and two additional studies were used only in a sensitivity analysis. The re-screened study of Dhandapani et al. [4] was obtained as an author-posted accepted manuscript and was included.

3.2 Characteristics of included studies

Table S1 in the Supplementary material summarizes the included studies [4,20–43] and the two sensitivity-only studies [44,45]. Nineteen studies investigated calcined clays (binary CC or LC3-type ternary blends) and six investigated metakaolin. Materials included normal concrete, self-compacting concrete, high-strength concrete and mortar, with w/b between 0.29 and 0.55 where stated. The CC or MK content ranged from 5% to 50% of the binder. The reported kaolinite content of the clays ranged from 0% (an illitic common clay) to 95%. In total, the pooled analyses comprised 30 CC/MK mixes for Dnssm, 51 for RCPT, 12 for Da and 9 for accelerated carbonation. Fifteen studies required figure digitization or the reading of printed data labels for at least one outcome. Most studies reported neither SDs nor replicate numbers, and the test age was unstated or inconsistent in four. The evidence base is

recent: 19 of the 25 studies were published in 2022 or later. Seven studies appeared in MDPI journals, six in Elsevier journals and four in Springer Nature journals; the remaining eight appeared in other journals, conference outlets or repositories. This distribution partly reflects the open-access restriction of the search.

3.3 Chloride migration coefficient

Twelve studies (9 CC, 3 MK) reported Dnssm for CC/MK and PC mixes (Fig. 1). The pooled RR was 0.40 (95% CI 0.29–0.55), corresponding to a 60% reduction in the migration coefficient. Heterogeneity was high ($I^2 = 98\%$, $\tau^2 = 0.322$), and the 95% PI ranged from 0.11 to 1.49. In a new study of similar design the effect could therefore range from a large reduction to no difference. Study-level ratios ranged from 0.10 to 1.00. The strongest effect (RR 0.10) came from the LC3 concretes of Dhandapani et al. [4], which were compared with OPC concretes of equal w/b in three mix series; without this study the pooled RR was 0.45. The only null result came from a self-compacting concrete with a Portland-limestone control, for which the value was approximate. The DerSimonian–Laird estimate had the same point value (0.40, 0.27–0.59).

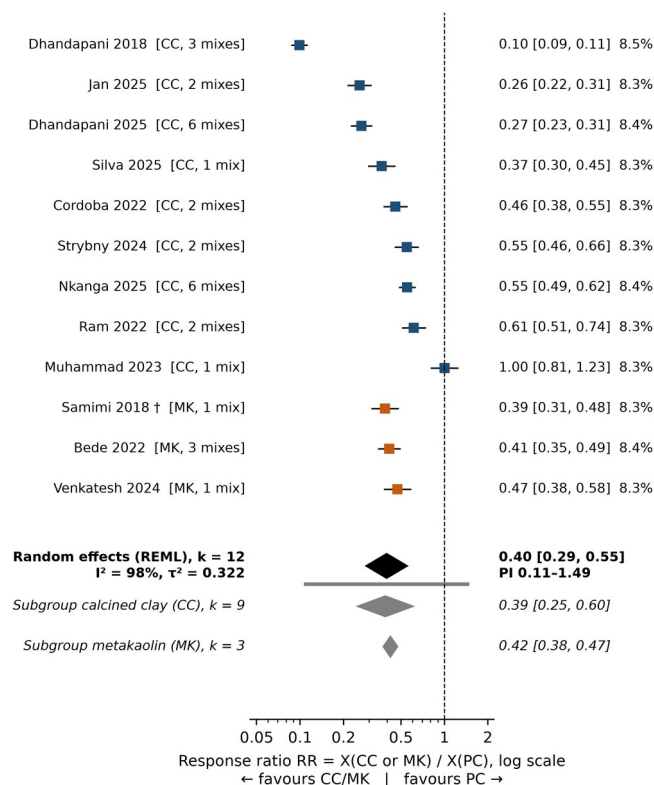


Fig. 1 Forest plot of the response ratio for the non-steady-state chloride migration coefficient (NT BUILD 492). Squares: study estimates (size proportional to random-effects weight) with 95% CI; blue = calcined clay, orange = metakaolin. Black diamond: pooled REML estimate; grey bar: 95% prediction interval; grey diamonds: subgroup estimates. † low-credibility venue. Variances are based on imputed CVs (Section 2.6)

3.4 Rapid chloride permeability (charge passed)

Twelve studies (8 CC, 4 MK) reported RCPT charge passed (Fig. S2 in the Supplementary material). The pooled RR was 0.36 (95% CI 0.23–0.56) (64% reduction), with $I^2 = 99\%$, $\tau^2 = 0.611$ and a PI of 0.06–2.20. The weakest effects (RR 0.83–0.88) were found for a self-compacting concrete with 5–15% calcined clay and for mortars with a low-grade clay of 17% kaolinite. The strongest effects were for the LC3 concretes of Dhandapani et al. (RR 0.05; 98–123 C against 2040–2635 C for OPC at 28 days) [4] and for an LC3-50 concrete made with a clay of 75% kaolinite (RR 0.19). Without the former study the pooled RR was 0.43.

3.5 Apparent chloride diffusion coefficient

Five CC studies reported D_a from bulk diffusion or ponding (Fig. S3 in the Supplementary material). The pooled RR was 0.28 (95% CI 0.13–0.61) (72% reduction). Heterogeneity was extreme ($I^2 = 99\%$, $\tau^2 = 0.788$), and the PI (0.01–6.17) was too wide to be informative. Much of the dispersion came from the kaolinite-gradient study of Maraghechi et al. [26], in which LC3 mortars with kaolinite contents of 50% and above reduced D_a by more than an order of magnitude after one year of exposure. Adding the two studies with migration-derived D_{app} [44,45] gave an RR of 0.29 (0.17–0.51; $k = 7$).

3.6 Carbonation

Five CC studies reported accelerated carbonation depths for CC and PC mixes under identical exposure (Fig. 2). Because the depths were compared at equal exposure time,

the ratio of depths equals the ratio of carbonation coefficients. The pooled RR was 2.09 (95% CI 1.43–3.07), meaning that the carbonation front advanced about twice as fast in CC mixes. Heterogeneity was high ($I^2 = 94\%$), and the PI (0.47–9.21) included unity. Study ratios ranged from 1.12 for LC3 mortars compared with a Portland-limestone (CEM II) control [28] to 3.62 for LC3 concretes compared with CEM I (natural-aggregate series of a recycled-aggregate study) [24]. This estimate is exploratory: the CV of 15% was assumed, $k = 5$ is at the minimum pooling threshold, one study used a Portland-limestone control, and in one study the percentage stated in the text contradicted the printed data labels (the labels were used) [34]. Accelerated tests at elevated CO_2 concentrations may also exaggerate differences between binders compared with natural exposure [9].

Natural carbonation could not be pooled. Cordoba et al. [23] reported natural carbonation coefficients after up to 36 months of rural exposure (7 days of curing) of 1.27 mm/yr^{0.5} for CEM I concrete, compared with 3.49 and 3.22 mm/yr^{0.5} for concretes with 25% of an illitic and a kaolinitic calcined clay, respectively, which are ratios of 2.7 and 2.5. In a marine field study in Salinas, Ecuador [46], natural carbonation depths after 24 months were 5.2 mm for LC3-50 and 1.0 mm for the PC reference. In contrast, field cores from a calcined clay–limestone concrete showed no major difference in carbonation depth from the PC concrete at RH above 80% [47]. This contrast is consistent with the known moisture dependence of carbonation [9,10].

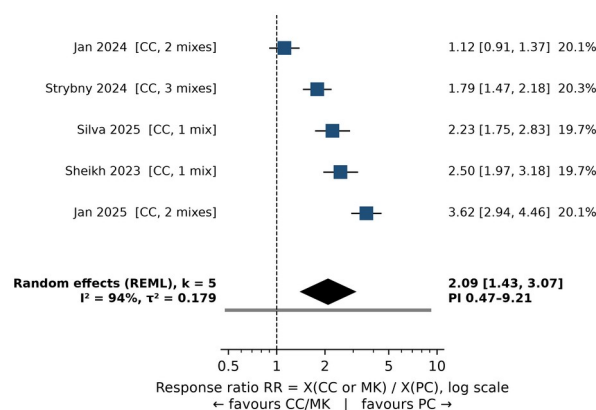


Fig. 2 Forest plot of the response ratio for accelerated carbonation depth (exploratory; CV of 15% assumed); RR > 1 indicates faster carbonation of the calcined clay mix; symbols as in Fig. 1

Table 1 Pooled random-effects (REML) estimates of the response ratio $RR = X(CC/MK)/X(PC)$

Outcome	Subgroup	k	Mixes	RR [95% CI]	Change (%)	τ^2	I^2 (%)	95% PI	CC vs MK p
Chloride migration Dnssm	All	12	30	0.40 [0.29, 0.55]	-60	0.322	98	0.11–1.49	0.73
	CC	9	25	0.39 [0.25, 0.60]	-61	0.440	99	0.07–2.04	

	MK	3	5	0.42 [0.38, 0.47]	-58	0.000	0	0.21–0.87	
RCPT charge passed	All	12	51	0.36 [0.23, 0.56]	-64	0.611	99	0.06–2.20	0.47
	CC	8	40	0.33 [0.17, 0.64]	-67	0.919	100	0.03–3.96	
	MK	4	11	0.42 [0.35, 0.52]	-58	0.035	84	0.17–1.07	
Apparent diffusion Da	All (CC)	5	12	0.28 [0.13, 0.61]	-72	0.788	99	0.01–6.17	—
	+ migration-derived Dapp	7	16	0.29 [0.17, 0.51]	-71	0.537	99	0.04–2.21	—
Accelerated carbonation (exploratory)	All (CC)	5	9	2.09 [1.43, 3.07]	+109	0.179	94	0.47–9.21	—

RR < 1 means lower chloride transport (beneficial); RR > 1 for carbonation means a faster carbonation front. Variances based on imputed CVs (13% Dnssm, 12.3% RCPT, 13% Da, 15% carbonation) with n = 3 per arm. PI, prediction interval. Subgroup p from a z-test of CC vs MK.

3.7 Calcined clay versus metakaolin

The subgroup estimates for CC and MK did not differ significantly (Table 1). For Dnssm the RR was 0.39 (0.25–0.60) for CC and 0.42 (0.38–0.47) for MK ($p = 0.73$). For RCPT it was 0.33 (0.17–0.64) for CC and 0.42 (0.35–0.52) for MK ($p = 0.47$). The MK subgroup was less heterogeneous ($I^2 = 0\%$ for Dnssm with three studies; 84% for RCPT). The CC subgroup combined clays of very different quality, from illitic clays to clays with 75% kaolinite, and included the strongest single effects. No MK study reported accelerated carbonation or Da.

3.8 Effect of kaolinite content

The combined meta-regression (Model A) included 43 comparisons from 9 studies (16 Dnssm, 18 RCPT, 9 Da). Each 10 pp increase in kaolinite content changed lnRR by -0.355 (95% CI -0.530 to -0.179), so the RR was multiplied by 0.70 (0.59–0.84) (Fig. 3, Table 2). Dhandapani et al. [4]

did not report the kaolinite content of their clay and therefore did not enter the meta-regression. The within-study estimate (Model B, 7 studies with more than one kaolinite level) was steeper: -0.456 per 10 pp (-0.633 to -0.280), or a factor of 0.63 (0.53–0.76). By outcome, the slope was significant for RCPT (-0.384, -0.658 to -0.110; 4 studies) and Da (-0.562, -0.667 to -0.458; 3 studies) but not for Dnssm (-0.165, -0.508 to 0.177; 4 studies). The fitted lines approach or exceed RR = 1 at kaolinite contents below roughly 10–20%, which suggests that low-grade clays may offer little or no chloride advantage over PC. This is consistent with the null or adverse results observed for an illitic clay at 28 days [23] and for clays with about 17% kaolinite [31]. These estimates should be read as exploratory, because the number of clusters is small and kaolinite content was not defined in the same way across studies.

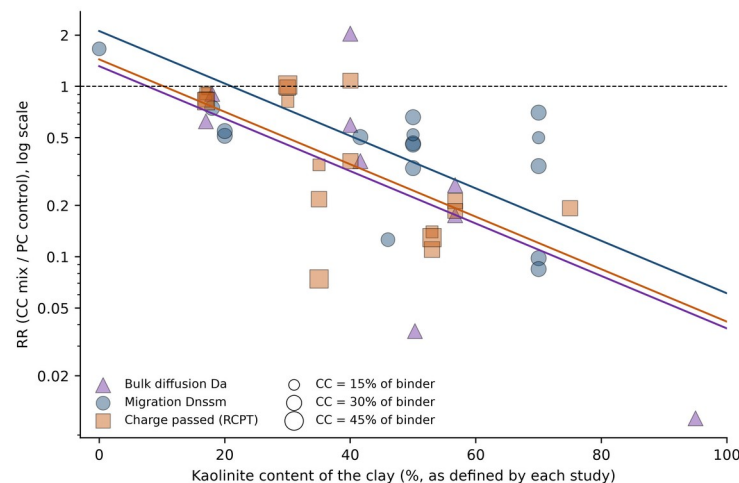


Fig. 3 Comparison-level response ratio for chloride outcomes versus the kaolinite content of the clay (calcined clay studies only); marker area is proportional to the calcined clay content of the binder; lines show Model A fits (common slope, outcome-specific intercepts; 0.70× per +10 pp, 9 studies, 43 comparisons); kaolinite content as defined by each study

Table 2 Exploratory meta-regression of the chloride response ratio on clay kaolinite content (calcined clay studies only)

Model	Outcomes	Studies (comparisons)	Slope, lnRR per +10 pp [95% CI]	RR factor per +10 pp
A: outcome dummies, cluster-robust (CR1)	Dnssm, RCPT, Da	9 (43)	-0.355 [-0.530, -0.179]	0.70 [0.59, 0.84]
B: within-study (study × outcome	Dnssm, RCPT, Da	7	-0.456 [-0.633, -0.280]	0.63 [0.53, 0.76]

fixed effects)				
Single outcome, cluster-robust	Dnssm	4 (15)	-0.165 [-0.508, 0.177]	0.85 [0.60, 1.19]
Single outcome, cluster-robust	RCPT	4 (18)	-0.384 [-0.658, -0.110]	0.68 [0.52, 0.90]
Single outcome, cluster-robust	Da	3 (9)	-0.562 [-0.667, -0.458]	0.57 [0.51, 0.63]

Model A has a common slope with outcome-specific intercepts. Model B uses only studies with more than one kaolinite level. 95% CIs are t-based with $G - 1$ degrees of freedom (G = number of studies). Kaolinite definitions differ between studies.

3.9 Sensitivity and robustness

The direction of the pooled chloride estimates was robust to the analytical choices tested, but their magnitude depended on a single influential study (Table S2 in the Supplementary material). Using reported or digitized SDs left the Dnssm, RCPT and Da estimates unchanged to two decimals. Excluding low-credibility venues, approximate values and comparisons with an unclear test age strengthened the effects (Dnssm 0.36, $k = 9$; RCPT 0.27, $k = 7$). Leave-one-out estimates ranged from 0.37 to 0.45 for Dnssm and from 0.33 to 0.43 for RCPT; in both cases the upper value was obtained when Dhandapani et al. [4] was omitted, which returns the estimates to those obtained before this study was added. For Da, leave-one-out estimates ranged from 0.23 to 0.40, the upper value being obtained when the kaolinite-gradient study was omitted. The carbonation estimate varied between 1.82 and 2.45 in the leave-one-out analysis. Formal small-study or publication-bias tests (for example, Egger's test) were not performed, because there were at most 12 studies per outcome and the imputed variances were nearly equal across studies, so funnel-plot asymmetry could not be interpreted meaningfully.

3.10 Narrative evidence

Several studies supported the direction of the pooled chloride results but could not be pooled. Colorimetric (AgNO_3) chloride penetration depths were 38–42% lower for an LC3 mortar than for its PC-based control after 84 days of immersion [48]. They were also lower for LC3-50 and LC3-70 mortars (3.8–7.9 mm) than for a Portland-limestone mortar (11.5–22.3 mm) [28]. In engineered cementitious composites with recycled fine aggregate, LC3 reduced near-surface chloride concentrations by 47–71%

[49]. Field cores from a calcined clay–limestone concrete showed surface resistivity and formation factors two to three times higher than those of PC concrete, and chloride contents about half as high [47]. In the Ecuador field study, tidal-zone cores of LC3 concrete had a migration coefficient of $0.22 \times 10^{-12} \text{ m}^2/\text{s}$ after 24 months, compared with $3.47 \times 10^{-12} \text{ m}^2/\text{s}$ for the PC reference [46]. In the same study as the pooled migration and RCPT data, the Wenner resistivity of LC3 concretes at 28 days was 228–299 $\text{k}\Omega\cdot\text{cm}$, against 11–16 $\text{k}\Omega\cdot\text{cm}$ for OPC concretes [4].

4 Service-life implications for Indian exposure classes

4.1 Inputs

Table 3 lists the inputs of the illustrative calculation. The PC reference migration coefficient of $12.0 \times 10^{-12} \text{ m}^2/\text{s}$ is the median of six 28-day CEM I or OPC concrete controls from the included studies (range $9.2\text{--}14.2 \times 10^{-12} \text{ m}^2/\text{s}$). The ageing exponent (mean $a = 0.30$ for Portland cement concrete), the critical chloride content (mean 0.6 wt.% of binder), the reference age (28 d), the regression variable of the temperature factor ($b_e = 4800 \text{ K}$, $T_{\text{ref}} = 293 \text{ K}$), the transfer parameter ($k_t = 1$) and the mean depth of the convection zone for splash and tidal conditions ($\Delta x = 8.9 \text{ mm}$) are the mean values of the full-probabilistic model of fib Bulletin 34 [13]. The Bulletin sets $\Delta x = 0$ for submerged and spray conditions, so $\Delta x = 8.9 \text{ mm}$ was applied only to the extreme (tidal-zone) class. A mean annual temperature of 27°C was assumed for Indian coastal sites ($k_e = 1.47$). Surface chloride contents of 1.0, 2.0, 3.0 and 4.0 wt.% of binder were assigned to the moderate, severe, very severe and extreme classes of IS 456 [7]. These are assumed scenario values chosen only to span a plausible range, not data from Indian structures. The IS 456 nominal covers (30, 45, 50 and 75 mm) were used for comparison.

Table 3 Inputs to the illustrative mean-value chloride service-life calculation (fib Bulletin 34 model, Eqs. (3)–(6))

Parameter	Value used	Source / status
DRCM,0, PC concrete (28 d)	$12.0 \times 10^{-12} \text{ m}^2/\text{s}$ (range 9.2–14.2)	DATA: median of six CEM I/OPC concrete controls, w/b 0.40–0.50, one per study [4,20–24]
DRCM,0, CC/MK concrete	$\text{RR} \times \text{DRCM,0(PC)}$; $\text{RR} = 0.40$ [0.29, 0.55]; upper PI 1.49	DATA: this meta-analysis (Table 1)
Ageing exponent a	0.30 for both binders (base); 0.45 for CC/MK (sensitivity)	fib Bulletin 34 means: Portland cement concrete 0.30 (beta, SD 0.12, 0–1); slag concrete 0.45 (SD 0.20), applied to CC/MK only as a hypothetical case [13]
Reference age t_0	28 d (0.0767 yr)	fib Bulletin 34 [13]
Transfer parameter k_t	1	fib Bulletin 34 (with DRCM,0 from NT BUILD 492) [13]
Temperature factor k_e	$b_e = 4800 \text{ K}$, $T_{\text{ref}} = 293 \text{ K}$, $T_{\text{real}} = 300 \text{ K} \rightarrow k_e = 1.47$	b_e (normal, SD 700 K) and T_{ref} : fib Bulletin 34 [13]; $T_{\text{real}} = 27^\circ\text{C}$ ASSUMED as a mean annual temperature for Indian

Critical chloride content C_{crit}	0.6 wt.% of binder	coastal sites fib Bulletin 34 mean (beta, SD 0.15, 0.2–2.0 wt.%) [13]
Initial chloride content C_0	0	ASSUMED (chloride-free constituents)
Surface chloride content C_s	Moderate 1.0; severe 2.0; very severe 3.0; extreme 4.0 wt.% of binder	ASSUMED scenario values spanning a plausible range; not measured data
Convection zone Δx	0 mm (moderate, severe, very severe); 8.9 mm (extreme, tidal zone)	fib Bulletin 34: $\Delta x = 0$ for submerged and spray conditions; splash/tidal mean 8.9 mm (beta, SD 5.6 mm, 0–50 mm) [13]
Nominal cover (comparison)	30 / 45 / 50 / 75 mm	IS 456:2000, Table 16 [7]
Design life	50 and 100 years	Illustrative

DATA = derived from included studies; ASSUMED = assumption made for illustration. Only the mean values of the fib distributions were used (deterministic calculation).

4.2 Required cover for chloride-induced corrosion

Fig. 4 and Table 4 show the cover at which the mean chloride content at the steel reaches C_{crit} at the end of a 50- or 100-year design life. Because Eq. (6) scales with the square root of D_{app} , the cover depth beyond Δx scales with $\sqrt{RR}$ when the ageing exponent is unchanged. The pooled RR of 0.40 therefore reduces the required cover by a factor of 0.63, that is by more than one third. For the very severe class and 50 years, for example, the mean-value cover fell from 114 mm for PC to 72 mm for CC/MK (61–85 mm across the CI of the RR). For the severe class it fell from 92 to 58 mm.

Three observations qualify this result. First, with the fib ageing exponent for CEM I and the assumed surface chloride contents, the mean-value covers for PC exceed the IS 456 nominal covers in every class. For CC/MK, the cover

approached the nominal value only for the moderate class (30 mm against 30 mm at 50 years). This reflects the conservative ageing assumption and the high temperature factor as much as the binder. Second, at the upper limit of the prediction interval (RR 1.49) the advantage disappears. A new CC/MK concrete therefore cannot be assumed to perform better without testing, which points to performance-based acceptance. Third, the ageing exponent dominates the outcome. If CC/MK concretes aged like slag concretes ($a = 0.45$, a hypothetical value), the required cover for the very severe class at 50 years would fall further, to 44 mm. For the extreme class at 100 years it would fall from 112 mm to 69 mm. Measured long-term migration or diffusion data for LC3-type concretes are therefore the most valuable missing input.

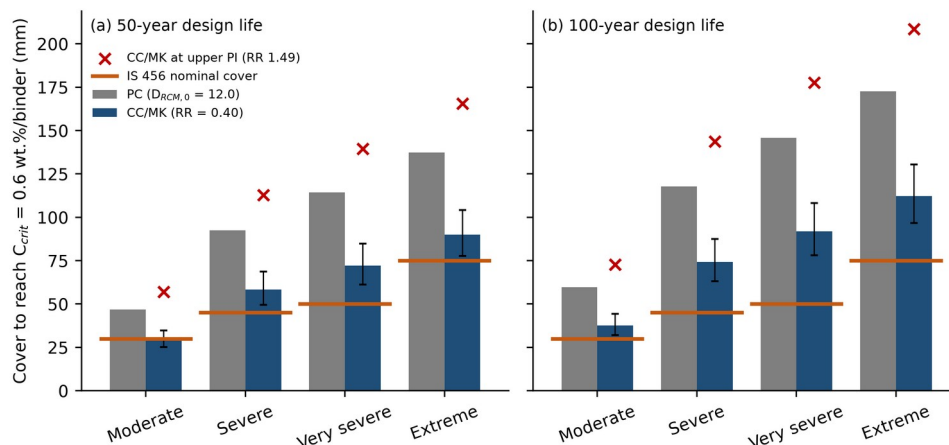


Fig. 4 Illustrative mean-value cover required for the chloride content at the reinforcement to reach $C_{crit} = 0.6$ wt.% of binder at the end of a (a) 50-year and (b) 100-year design life, for PC ($D_{RCM,0} = 12.0 \times 10^{-12}$ m²/s) and CC/MK concrete (pooled RR 0.40; error bars: 95% CI of RR; crosses: upper limit of the 95% prediction interval); horizontal lines: IS 456 nominal cover; surface chloride contents are assumed scenario values (Table 3), and the same ageing exponent $a = 0.30$ is used for both binders

Table 4 Illustrative mean-value cover (mm) at which the chloride content at the steel reaches $C_{crit} = 0.6$ wt.% of binder at the end of the design life

IS 456 class	C_s (wt. %)	Life (yr)	Nominal cover (mm)	PC (mm)	CC/MK, RR 0.40 (mm)	CC/MK, RR CI (mm)	CC/MK, upper PI (mm)	CC/MK, $a =$ 0.45 (mm)
Moderate	1.0	50	30	47	30	25–35	57	18
Moderate	1.0	100	30	60	38	32–44	73	22

Severe	2.0	50	45	92	58	50–69	113	36
Severe	2.0	100	45	118	74	63–87	144	43
Very severe	3.0	50	50	114	72	61–85	139	44
Very severe	3.0	100	50	146	92	78–108	178	54
Extreme	4.0	50	75	137	90	78–104	165	59
Extreme	4.0	100	75	173	112	97–130	208	69

Not a design recommendation. $\alpha = 0.30$ for both binders unless stated; ' $\alpha = 0.45$ ' is a hypothetical sensitivity case for CC/MK. Cs values are assumed scenarios (Table 3).

4.3 Carbonation-induced corrosion

For carbonation, the depth grows with the square root of time, $x = k \cdot \sqrt{t}$. A carbonation coefficient ratio of 2.09 therefore requires a cover 2.09 times larger for the same time to depassivation. For an unchanged cover, it shortens the time to depassivation by a factor of 4.4. Taking the natural carbonation coefficient of the CEM I concrete reported by Cordoba et al. [23] ($1.27 \text{ mm/yr}^{0.5}$) as an illustration, the 50-year carbonation depth would be 9 mm for PC and 19 mm (13–28 mm) for CC when the pooled ratio is applied. The calcined clay concretes in that study themselves reached 23–25 mm after 50 years and 32–35 mm after 100 years. These depths exceed the IS 456 nominal cover of 20 mm for the mild class at 50 years and of 30 mm for the moderate class at 100 years. The comparison suggests that, in sheltered and drier inland exposures, carbonation rather than chloride ingress may govern cover for CC concretes. It is based on a single natural-exposure study with only 7 days of curing and does not account for the role of moisture in corrosion propagation [10].

4.4 Interpretation for Indian specifications

The analysis supports two practical conclusions. In chloride exposures (the severe, very severe and extreme classes), CC and MK concretes made with kaolinite-rich clays can be expected to reduce chloride transport substantially. This could justify performance-based relaxation of cover or w/b, but only if migration testing at the project stage confirms that the actual mix performs as expected. In carbonation-dominated exposures (the mild and moderate classes, inland and sheltered), the same binders may need more cover, longer curing or a lower w/b than PC concrete to achieve an equivalent service life. Both conclusions argue for complementing the IS 456 tables with performance criteria (for example, limiting values of D_{nssm} and of the carbonation coefficient) for concretes made with IS 18189 cement [6]. This is consistent with earlier service-life assessments of Indian LC3 concrete [5].

5 Discussion

5.1 Mechanisms behind the pooled trends

The consistent reduction of chloride transport and the steep dependence on kaolinite content agree with the

mechanisms identified in the RILEM TC 282-CCL review [8]. Metakaolin reacts with portlandite to form additional C-A-S-H. With limestone, it also forms carboaluminate AFm phases [1,2]. Both processes refine the capillary pore structure and increase the capacity of the binder to bind chlorides. The magnitude of these effects scales with the amount of reactive metakaolin, which is why low-kaolinite clays perform close to PC and why the kaolinite-gradient study showed such large reductions in diffusion at high kaolinite contents [26]. The same reactions consume portlandite, so the remaining CO_2 -binding capacity is lower and the carbonation front advances faster [9]. The two pooled results are therefore two consequences of the same chemistry.

5.2 Agreement between test methods

The three chloride indicators gave consistent directions and similar magnitudes for D_{nssm} and RCPT (RR 0.40 and 0.36). The larger effect for Da (RR 0.28) may reflect longer exposure, during which the continuing pozzolanic reaction and chloride binding act, but it rests on only five studies dominated by one experiment. The RCPT is an electrical test that is sensitive to pore-solution conductivity, which changes when SCMs are added. Its agreement with the migration results is therefore reassuring but should not be taken as independent confirmation of transport properties. For design, the migration coefficient is preferred because it enters the fib model directly [13].

5.3 Relation to previous work

The RILEM reviews concluded qualitatively that calcined clay systems improve chloride resistance and reduce carbonation resistance [8,9]. The present analysis adds magnitudes with uncertainty, shows that most of the variation in the chloride benefit is associated with kaolinite content, and makes explicit that the prediction intervals are wide.

For specification, the results suggest a two-step approach. First, the calcined clay should be qualified by its kaolinite content or reactivity (for example, with the R3 test [3]), since this is the strongest identified predictor of chloride performance. Second, the concrete should be qualified by mix-specific migration and carbonation tests,

with acceptance values derived from a service-life model rather than from the binder type alone. Because the prediction intervals are wide, neither binder type nor clay grade alone is sufficient evidence of performance. The same logic applies to Portland cement concretes, but the larger spread of calcined clay quality makes it particularly important for LC3-type binders.

5.4 Certainty of the evidence

A formal GRADE assessment is not established for materials-testing evidence. Applying its logic informally, the certainty is moderate for the direction of the chloride benefit. All three chloride indicators agree, the result survives every sensitivity analysis, and it is supported by field and colorimetric evidence. The certainty is low for its magnitude, because heterogeneity is very high, a single study shifts the pooled ratios noticeably, dispersion was imputed and the literature retrieved is incomplete. For the carbonation penalty, certainty is low in both direction and magnitude. Only five accelerated studies were available, the CV was assumed, and the natural-exposure evidence was inconsistent between exposure sites. The kaolinite dose–response relation is physically plausible, because it follows directly from the amount of reactive phase. It is supported by both between-study and within-study estimates, but its certainty is low because it rests on few clusters and mixed definitions of kaolinite content.

5.5 Limitations

The results must be interpreted with the following limitations in mind.

(i) Imputed dispersion. Most studies did not report SDs or replicate numbers. Sampling variances were derived from assumed CVs (13% for Dnssm and Da, 12.3% for RCPT and 15% for carbonation) and an assumed $n = 3$ per arm. The CVs for Da and carbonation are not supported by a verified precision statement. The sensitivity analysis with reported SDs gave the same point estimates, but confidence intervals depend on these assumptions.

(ii) Digitized data. Many values were digitized from figures. Double digitization with independent calibrations limits, but does not remove, reading error. Some values were derived from reported percentage changes or from printed data labels that conflicted with the text.

(iii) Open-access-only retrieval and screening. Only open-access full texts were used. Of the 426 reports sought, 152 closed-access reports could not be obtained, 144 open-access reports were still awaiting manual retrieval, and 75 retrieved reports were still being assessed. Scopus and Web

of Science were not searched. The rule-based first screening pass wrongly excluded at least two eligible records that lacked an abstract [4,12]; both were re-screened by hand, but the remaining rule-based exclusions of records without an abstract were not re-screened individually. The evidence base is therefore incomplete, and the results may not be representative of the full literature.

(iv) Credibility of sources. Three included studies were published in venues of low editorial credibility, one study was a conference extended abstract and one an accepted manuscript. Excluding the low-credibility studies did not weaken the chloride results.

(v) Differing kaolinite definitions. Kaolinite content was reported for the raw clay, for the calcined clay or as metakaolinite content, so the meta-regression mixes definitions that are not strictly comparable. It also relies on only 9 studies (7 for the within-study model).

(vi) Heterogeneity and influence. I^2 was between 94% and 99% for all primary analyses, and every prediction interval included $RR = 1$. One study with very low charge passed and migration coefficients for LC3 [4] moved the pooled Dnssm and RCPT ratios from 0.45 and 0.43 to 0.40 and 0.36. Test age, w/b, curing, material type and replacement level differed between studies, and with the present number of studies these moderators could not be separated from kaolinite content.

(vii) Carbonation. The carbonation estimate is exploratory: $k = 5$, an assumed CV, one Portland-limestone control, and accelerated rather than natural exposure.

(viii) Service-life model. The calculation uses mean values, assumed surface chloride contents and the same ageing exponent for both binders, and it is not a reliability-based design. It illustrates sensitivity to the pooled ratio and must not be used to set cover.

5.6 Research needs

The most useful additions to the evidence base would be: (i) long-term migration or diffusion data from which LC3-specific ageing exponents can be derived; (ii) natural carbonation data from Indian climates, with curing and moisture conditions reported; (iii) studies on low-grade Indian clays that report the kaolinite content measured by a common method; (iv) full reporting of means, SDs and replicate numbers in tables, which would remove the need for imputation and digitization; and (v) combined chloride–carbonation exposure and LC3 concretes with recycled aggregates, which were represented here by only two studies [24,49]. Updating this meta-analysis once the

pending full texts have been retrieved and assessed should narrow the confidence intervals and allow a multilevel model and a probabilistic service-life analysis with target reliability.

6 Conclusions

1. Across 25 studies, calcined clay and metakaolin binders reduced the chloride migration coefficient by 60% (RR 0.40 (95% CI 0.29–0.55); 12 studies), the RCPT charge passed by 64% (RR 0.36 (95% CI 0.23–0.56); 12 studies) and the apparent diffusion coefficient by 72% (RR 0.28 (95% CI 0.13–0.61); 5 studies) relative to Portland cement controls.

2. Accelerated carbonation depth was approximately doubled (RR 2.09 (95% CI 1.43–3.07); 5 studies). This estimate is exploratory, and natural-exposure evidence was limited but pointed in the same direction except in a humid field exposure.

3. Heterogeneity was high (I^2 94–99%), all prediction intervals included no effect, and one study had a marked influence on the chloride estimates. The benefit of a given mix should therefore be confirmed by testing rather than assumed.

4. Calcined clays and metakaolin gave statistically indistinguishable chloride benefits. Kaolinite content explained part of the variation: each 10 percentage points multiplied the chloride response ratio by 0.70 (0.59–0.84), or by 0.63 within studies, and low-grade clays (below roughly 20% kaolinite) offered little or no benefit in several studies.

5. In an illustrative fib Bulletin 34 calculation with identical ageing assumptions, the pooled migration ratio reduced the cover required against chloride-induced depassivation by more than one third. The ageing exponent of LC3-type concretes is the input with the greatest influence and the greatest uncertainty.

6. For Indian practice, IS 18189 concretes made with kaolinite-rich clays are promising for chloride exposures, but carbonation may govern in mild and moderate exposures. Performance-based limits on migration and carbonation coefficients would allow these binders to be specified safely.

Data availability

The extracted dataset and analysis scripts are provided as supplementary material. Tables S1 and S2 (characteristics of the included studies; sensitivity analyses) and Figs. S1–S3 (PRISMA 2020 flow diagram; forest plots for charge

passed and for the bulk-diffusion coefficient) are provided in a separate supplementary file.

Declaration of generative AI use

During the preparation of this work the author used an AI assistant (Grok Bot) to help write the search, screening, extraction-support, digitization and analysis scripts, to assist with data extraction and figure digitization, and to draft and edit the manuscript text. No data were generated by AI: every numerical value used in the analysis was taken from the cited publications and is traceable to a specific page, table or figure in the supplementary dataset, and a stratified sample of about 10% of the extracted values was checked against the source documents. Imputed dispersion values and all service-life inputs are identified as assumptions. The author reviewed and edited the content and takes full responsibility for the published article.

Conflict of interest

The author declares no conflict of interest. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

- [1] Antoni, M., Rossen, J., Martirena, F., Scrivener, K. "Cement substitution by a combination of metakaolin and limestone", *Cement and Concrete Research*, 42(12), pp. 1579–1589, 2012. <https://doi.org/10.1016/j.cemconres.2012.09.006>
- [2] Scrivener, K., Martirena, F., Bishnoi, S., Maity, S. "Calcined clay limestone cements (LC3)", *Cement and Concrete Research*, 114, pp. 49–56, 2018. <https://doi.org/10.1016/j.cemconres.2017.08.017>
- [3] Avet, F., Snellings, R., Alujas Diaz, A., Ben Haha, M., Scrivener, K. "Development of a new rapid, relevant and reliable (R3) test method to evaluate the pozzolanic reactivity of calcined kaolinitic clays", *Cement and Concrete Research*, 85, pp. 1–11, 2016. <https://doi.org/10.1016/j.cemconres.2016.02.015>
- [4] Dhandapani, Y., Sakthivel, T., Santhanam, M., Gettu, R., Pillai, R. G. "Mechanical properties and durability performance of concretes with Limestone Calcined Clay Cement (LC3)", *Cement and Concrete Research*, 107, pp. 136–151, 2018. <https://doi.org/10.1016/j.cemconres.2018.02.005>
- [5] Pillai, R. G., Gettu, R., Santhanam, M., Rengaraju, S., Dhandapani, Y., Rathnarajan, S., Basavaraj, A. S. "Service life and life cycle assessment of reinforced concrete systems with limestone calcined clay cement (LC3)", *Cement and Concrete Research*, 118, pp. 111–119, 2019. <https://doi.org/10.1016/j.cemconres.2018.11.019>
- [6] Bureau of Indian Standards "IS 18189:2023 Portland calcined clay limestone cement – Specification", BIS, New Delhi, India, 2023.
- [7] Bureau of Indian Standards "IS 456:2000 Plain and reinforced concrete – Code of practice (Fourth revision)", BIS, New Delhi, India, 2000.
- [8] Dhandapani, Y., Machner, A., Wilson, W., Kunther, W., Afroz, S., Kim, T., Zunino, F., Joseph, S., Kanavaris, F., Castel, A., Thienel, K. -C., Irassar, E. F., Bishnoi, S., Martirena, F., Santhanam, M.

- "Performance of cementitious systems containing calcined clay in a chloride-rich environment: a review by TC-282 CCL", *Materials and Structures*, 57(7), 154, 2024. <https://doi.org/10.1617/s11527-024-02426-7>
- [9] von Greve-Dierfeld, S., Lothenbach, B., Vollpracht, A., Wu, B., Huet, B., Andrade, C., Medina, C., Thiel, C., Gruyaert, E., Vanoutrive, H., Saéz del Bosque, I. F., Ignjatovic, I., Elsen, J., Provis, J. L., Scrivener, K., Thienel, K. -C., Sideris, K., Zajac, M., Alderete, N., Cizer, Ö., Van den Heede, P., Hooton, R. D., Kamali-Bernard, S., Bernal, S. A., Zhao, Z., Shi, Z., De Belie, N. "Understanding the carbonation of concrete with supplementary cementitious materials: a critical review by RILEM TC 281-CCC", *Materials and Structures*, 53(6), 136, 2020. <https://doi.org/10.1617/s11527-020-01558-w>
- [10] Angst, U., Moro, F., Geiker, M., Kessler, S., Beushausen, H., Andrade, C., Lahdensivu, J., Köliö, A., Imamoto, K. -i., Von Greve-Dierfeld, S., Serdar, M. "Corrosion of steel in carbonated concrete: mechanisms, practical experience, and research priorities – a critical review by RILEM TC 281-CCC", *RILEM Technical Letters*, 5, pp. 85–100, 2020. <https://doi.org/10.21809/rilemtechlett.2020.127>
- [11] Khan, M. S. H., Nguyen, Q. D., Castel, A. "Performance of limestone calcined clay blended cement-based concrete against carbonation", *Advances in Cement Research*, 32(11), pp. 481–491, 2020. <https://doi.org/10.1680/jadcr.18.00172>
- [12] Zolfagharnasab, A., Ramezaniapour, A. A., Bahman-Zadeh, F. "Investigating the potential of low-grade calcined clays to produce durable LC3 binders against chloride ions attack", *Construction and Building Materials*, 303, 124541, 2021. <https://doi.org/10.1016/j.conbuildmat.2021.124541>
- [13] fib "Model Code for Service Life Design", fib Bulletin 34, International Federation for Structural Concrete, Lausanne, Switzerland, 2006. ISBN 978-2-88394-074-1. <https://doi.org/10.35789/fib.bull.0034>
- [14] Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., McGuinness, L. A., Stewart, L. A., Thomas, J., Tricco, A. C., Welch, V. A., Whiting, P., Moher, D. "The PRISMA 2020 statement: an updated guideline for reporting systematic reviews", *BMJ*, 372, n71, 2021. <https://doi.org/10.1136/bmj.n71>
- [15] Nordtest "NT BUILD 492 Concrete, mortar and cement-based repair materials: Chloride migration coefficient from non-steady-state migration experiments", Nordtest, Espoo, Finland, 1999.
- [16] ASTM International "ASTM C1202-22e1 Standard test method for electrical indication of concrete's ability to resist chloride ion penetration", ASTM International, West Conshohocken, PA, USA, 2022. <https://doi.org/10.1520/C1202-22E01>
- [17] ASTM International "ASTM C1556-25 Standard test method for determining the apparent chloride diffusion coefficient of cementitious mixtures by bulk diffusion", ASTM International, West Conshohocken, PA, USA, 2025.
- [18] CEN "EN 12390-12:2020 Testing hardened concrete – Part 12: Determination of the carbonation resistance of concrete – Accelerated carbonation method", European Committee for Standardization, Brussels, Belgium, 2020.
- [19] Hedges, L. V., Gurevitch, J., Curtis, P. S. "The meta-analysis of response ratios in experimental ecology", *Ecology*, 80(4), pp. 1150–1156, 1999. [https://doi.org/10.1890/0012-9658\(1999\)080\[1150:TMAORR\]2.0.CO;2](https://doi.org/10.1890/0012-9658(1999)080[1150:TMAORR]2.0.CO;2)
- [20] Ram, K., Flegar, M., Serdar, M., Scrivener, K. "Influence of Low- to Medium-Kaolinite Clay on the Durability of Limestone Calcined Clay Cement (LC3) Concrete", *Materials*, 16(1), pp. 374, 2022. <https://doi.org/10.3390/ma16010374>
- [21] Strybny, B., Schack, T., Link, J., Haist, M. "Calcined Clays as Concrete Additive in Structural Concrete: Workability, Mechanical Properties, Durability, and Sustainability Performance", *Materials*, 17(18), pp. 4517, 2024. <https://doi.org/10.3390/ma17184517>
- [22] Dhandapani, Y., Subramanian, K. K., Kanavaris, F., Black, L., Bernal, S. A. "The meta-kaolinite content of the calcined clay source impacts the mechanical and durability performance of blended Portland concrete", *Cement and Concrete Research*, 196, 107922, 2025. <https://doi.org/10.1016/j.cemconres.2025.107922>
- [23] Cordoba, G., Sposito, R., Köberl, M., Zito, S., Beuntner, N., Tironi, A., Thienel, K. -C., Irassar, E. F. "Chloride migration and long-term natural carbonation on concretes with calcined clays: A study of calcined clays in Argentina", *Case Studies in Construction Materials*, 17, e01190, 2022. <https://doi.org/10.1016/j.cscm.2022.e01190>
- [24] Jan, A., Ferrari, L., Neves, R., Franzoni, E., de Brito, J. "Durability and rheological properties of concrete with recycled fine and coarse aggregates and LC3", *Construction and Building Materials*, 498, 143993, 2025. <https://doi.org/10.1016/j.conbuildmat.2025.143993>
- [25] Nguyen, Q. D., Afroz, S., Castel, A. "Influence of Calcined Clay Reactivity on the Mechanical Properties and Chloride Diffusion Resistance of Limestone Calcined Clay Cement (LC3) Concrete", *Journal of Marine Science and Engineering*, 8(5), pp. 301, 2020. <https://doi.org/10.3390/jmse8050301>
- [26] Maraghechi, H., Avet, F., Wong, H., Kazemi-Kamyab, H., Scrivener, K. "Performance of Limestone Calcined Clay Cement (LC3) with various kaolinite contents with respect to chloride transport", *Materials and Structures*, 51(5), 125, 2018. <https://doi.org/10.1617/s11527-018-1255-3>
- [27] Abdulqader, M., Khalid, H. R., Ibrahim, M., Adekunle, S. K., Al-Osta, M. A., Ahmad, S., Sajid, M. "Physicochemical properties of limestone calcined clay cement (LC3) concrete made using Saudi clays", *Journal of Materials Research and Technology*, 25, pp. 2769–2783, 2023. <https://doi.org/10.1016/j.jmrt.2023.06.114>
- [28] Jan, A., Ferrari, L., Mikanovic, N., Ben-Haha, M., Franzoni, E. "Chloride ingress and carbonation assessment of mortars prepared with recycled sand and calcined clay-based cement", *Construction and Building Materials*, 456, 139337, 2024. <https://doi.org/10.1016/j.conbuildmat.2024.139337>
- [29] Nkanga, U., Dhandapani, Y., Pessu, F. O., Black, L. "Chloride-related durability properties of mortars and concrete containing calcined clay", In: Nguyen, V. T., Nguyen, T. D., Nguyen, T.-N. H., Phung, Q. T., Nguyen, T. L. (eds.) *Proceedings of the 79th RILEM Annual Week & ICONS 2025*, Hanoi, Vietnam, 2025, RILEM Bookseries, Springer, Cham, Switzerland (in press). ISBN 978-3-032-27918-7. [online] Available at: <https://eprints.whiterose.ac.uk/id/eprint/235942/> [Accessed: 16 October 2026]

- [30] Abdelfattah, A. R., Ragab, A., Elyamany, M., Younis, S. "Innovative Utilization of Limestone Calcined Clay Cement from the Egyptian Desert: Enhancing the Physico-Mechanical Properties for Sustainable Construction", *Civil Engineering and Architecture*, 13(1), pp. 237–256, 2025. <https://doi.org/10.13189/cea.2025.130114>
- [31] Boakye, K., Khorami, M. "Effect of Low-Grade Calcined Clay on the Durability Performance of Blended Cement Mortar", *Buildings*, 15(7), pp. 1159, 2025. <https://doi.org/10.3390/buildings15071159>
- [32] Dousti, A., Beyki, H., Shekarchi, M. "Strength and durability performance of mortars incorporating calcined clay as pozzolan in comparison with silica fume", *Journal of Civil Engineering and Materials Application*, 6(3), pp. 159–174, 2022. <https://doi.org/10.22034/jcema.2022.361685.1096>
- [33] Meddah, M. S., Abdel-Gawwad, H., Al Owaisi, M. "The role of low-quality calcined clay in enhancing the performance of cement mortar exposed to normal and aggressive media", *Scientific Reports*, 14(1), 23855, 2024. <https://doi.org/10.1038/s41598-024-74885-5>
- [34] Sheikh, M. D., Jamil, T., Ayub, T., Khan, A. -u. -R., Bilal, S. M., Hu, C. "Comparative Study on LC3-50 with OPC Concrete Using Raw Materials from Pakistan", *Advances in Materials Science and Engineering*, 2023, 5503670, 2023. <https://doi.org/10.1155/2023/5503670>
- [35] Bede Odorčić, N., Kravanja, G. "Combined Effects of Metakaolin and Hybrid Fibers on Self-Compacting Concrete", *Materials*, 15(16), pp. 5588, 2022. <https://doi.org/10.3390/ma15165588>
- [36] Asst.Prof., Dr.MGR Educational Research Institute University, Chennai, 600095, India., , Narmatha*, M., Muralikrishnan, S., Asts.Prof., Arignar Anna Institute of Science and Technology, Chennai, 602117, India, "Durability Properties of Kaolinite Clay - Metakaolin in Concrete", *International Journal of Recent Technology and Engineering (IJRTE)*, 8(6), pp. 3081–3086, 2020. <https://doi.org/10.35940/ijrte.f7281.038620>
- [37] Muhammad, A., Thienel, K. -C. "Properties of Self-Compacting Concrete Produced with Optimized Volumes of Calcined Clay and Rice Husk Ash—Emphasis on Rheology, Flowability Retention and Durability", *Materials*, 16(16), pp. 5513, 2023. <https://doi.org/10.3390/ma16165513>
- [38] Padavala, S. S. A. B., Ayudaippan, S., Yantrapalli, S. K., Kumara, A. M., Harinder, D., Paluri, Y. "Experimental evaluation, machine learning prediction, and life cycle assessment of sustainable self compacting concrete incorporating limestone powder and calcined clay", *Scientific Reports*, 2026 (in press; published online 22 July 2026). <https://doi.org/10.1038/s41598-026-63459-2>
- [39] Zeyad, A. M., Shah, A. M., Megat Johari, M. A., Mutnbak, M. "Influence of Steam Curing on the Performance of High-strength Concrete Incorporating Metakaolin", *Periodica Polytechnica Civil Engineering*, 68(4), pp. 1132–1148, 2024. <https://doi.org/10.3311/ppci.36571>
- [40] Kannan, V., Raja Priya, P. "Evaluation of the permeability of high strength concrete using metakaolin and wood ash as partial replacement for cement", *SN Applied Sciences*, 3(1), 90, 2021. <https://doi.org/10.1007/s42452-020-04024-y>
- [41] Samimi, K., Estakhr, F., Mahdikhani, M., Moodi, F. "Influence of metakaolin and cements types on compressive strength and transport properties of self-consolidating concrete", *Zenodo*, 2018. <https://doi.org/10.5281/zenodo.1315974>
- [42] Silva, L. H. P., Tamashiro, J. R., de Paiva, F. F. G., da Silva Rego, J. H., de la Rubia, M. A., Kinoshita, A., Terrades, A. M. "Durability Assessment of Binary and Ternary Eco-Friendly Mortars with Low Cement Content", *Solids*, 6(2), pp. 28, 2025. <https://doi.org/10.3390/solids6020028>
- [43] Chava, V., M.v., S. R., Munugala, P. K., Cherreddy, S. S. D. "Effect of Mineral Admixtures and Curing Regimes on Properties of Self-Compacting Concrete", *Journal of Sustainable Construction Materials and Technologies*, 9(1), pp. 25–35, 2024. <https://doi.org/10.47481/jscmt.1383493>
- [44] Marangu, J. M., Thiong'o, J. K., Wachira, J. M. "Chloride Ingress in Chemically Activated Calcined Clay-Based Cement", *Journal of Chemistry*, 2018, 1595230, 2018. <https://doi.org/10.1155/2018/1595230>
- [45] Marangu, J. M. "Physico-chemical properties of Kenyan made calcined Clay -Limestone cement (LC3)", *Case Studies in Construction Materials*, 12, e00333, 2020. <https://doi.org/10.1016/j.cscm.2020.e00333>
- [46] Garces-Vargas, J. F., Díaz-Cardenas, Y., Martirena Hernandez, J. F. "Evaluation of the Durability of Concrete with the Use of Calcined Clays and Limestone in Salinas, Ecuador", *Minerals*, 14(5), pp. 460, 2024. <https://doi.org/10.3390/min14050460>
- [47] Martirena, F., Díaz, E., Rocha, D., Maraghechi, H., Scrivener, K. L. "Performance of concrete made with a calcined clay – limestone-Portland cement exposed to natural conditions", In: *International Conference on Durability of Concrete Structures (ICDCS 2018)*, West Lafayette, IN, USA, 2018, Paper 21. Purdue e-Pubs, 2019. [online] Available at: <https://docs.lib.purdue.edu/icdcs/2018/icc/21> [Accessed: 16 October 2026]
- [48] Huang, G., Liu, Y., Benn, T., Ataabadi, H. S., Zhuge, Y. "The self-healing performance and mechanism of limestone calcined clay composites coupling with crystalline admixture in chloride-rich environments", *Construction and Building Materials*, 463, 140097, 2025. <https://doi.org/10.1016/j.conbuildmat.2025.140097>
- [49] Riaz, M. H., Zhou, Y., Guo, M., Kazmi, S. M. S., Zhu, Z., Shamim, A. "Mechanical properties and durability of ECC incorporating LC3 and RFA in chloride environment", *Case Studies in Construction Materials*, 23, e05520, 2025. <https://doi.org/10.1016/j.cscm.2025.e05520>