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Evolution of bond stress for low and high plastic clays with time

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ABSTRACT: Soft clays are ubiquitous and are often stabilized with cement to significantly enhance their mechanical properties. While numerous studies have examined the strength progression with time through a simple unconfined compressive strength (UCS) testing, a limited information is available on the evolution of interparticle bonds, which is essential for simulating the response of cement-stabilized clays through different constitutive models. The current study evaluates the evolution of bond strength of these stabilized clays through indirect tension test. Additionally, the SEM studies were conducted on the stabilized clay samples at different curing periods to substantiate the mechanical findings. The stabilized clay samples were cured for up to 200 days to assess the bond strength progression. The differences in cement dosage, binder type, remoulded water content, and curing temperature on the tensile strength development of low plastic and high plastic clays were examined. Depending on the rate of evolution in tensile strength and UCS, the cemented clay can be classified into active-bond enhanced and inactive-bond enhanced cemented clays. The classification was carried out through the asymptotic time for tensile strength and UCS for cement stabilized clays. The study examined the behaviour of various clays stabilized with Portland blast furnace slag cement (PBFC) and ordinary Portland cement (OPC) reported in the literature. In addition, BTS tests were performed on two clays stabilized with varying cement dosages and remoulded at different water contents to evaluate the degree of bond formation. Results indicate that clay plasticity plays a major role in determining the key parameter influencing the rate of strength gain in cement-stabilized clays. For low-plasticity clays, remoulding water content was the dominant factor affecting the rate of bond strength, whereas for high-plasticity clays, cement dosage had a greater influence on the evolution of bond strength. These results are crucial and provide a better understanding of the stabilization process in clays with cement.

KEYWORDS: Bond stress, ground improvement, Brazilian Tensile Strength.

1 INTRODUCTION

Marine deposits rich in clay are highly compressible in nature and generally exhibit low shear strength, making them unsuitable for construction (Ornek et al., 2012). However, with the rapid growth of population in coastal regions, the use of these soils has become increasingly unavoidable. Consequently, their stabilization becomes essential for construction purposes, with cement stabilization being one of the most widely adopted methods for improving such soils (Terashi, 1980; Miller and Azad, 2000; Cong et al., 2014). De Souza et al. (2022) suggested that the cement industry as a significant source of global carbon emissions, responsible for roughly 5–7% of anthropogenic CO_2 output, thereby exerting a considerable influence on climate change. Therefore, designing for the effective use of cement in cement-stabilized clay, or incorporating low-carbon emission binders, is crucial.

The enhancement in the strength of cemented clays is attributed to the primary hydration of cement, and pozzolanic reaction with amorphous clay particles (Chew et al., 2004). These reactions are highly sensitive to external factors such as temperature, and pH and contribute to the stiffness and the strength of cemented clays. The short-term strength gain is mainly influenced by the cement hydration, while the long-term strength is affected by the pozzolanic reaction. The key external factors influencing the cement hydration of cement stabilized clay are cement dosage, binder type, curing temperature and curing period (Neville, 1995; Morohoshi et al., 2010; Mindess and Sidney, 2019). However, the key factors influencing the pozzolanic reaction in cement-clay system is mainly influenced by clay mineralogy, curing period, curing temperature, remoulding water content, as well as pore pH (Zhang et al., 2014; Sukmak et al., 2023; Wu et al., 2024). For instance, Sukmak et al. (2023) examined the effect of clay mineralogy on the strength of cement-stabilized clays, revealing that samples with lower cation exchange capacity (CEC) required significantly less cement for strength improvement than those with higher CEC, owing to the greater amount of Ca^{2+} ions needed for complete hydration in the latter. Zhang et al. (2014) studied the effect of curing temperature on the strength development of cement-stabilized clays and reported that higher temperatures resulted in a significantly greater asymptotic unconfined compressive strength (UCS) and a shorter inflection time—contrary to the cross-over behaviour observed in concrete—by accelerating both cement hydration and the pozzolanic reaction. The study also explored the effect of binder type on the long-term strength of stabilized clay, with significantly higher inflection time for samples stabilized with Portland blast furnace slag cement (PBFC) binder as opposed to the samples stabilized with OPC. Similarly, Chitambira et al. (2007) examined the effects of elevated temperature on the strength of cement stabilized clays, and reported an increased rate of silicate polymerization, resulting in dense microstructure contributing to the strength increase. However, predicting the long-term strength of cement-stabilized clays remains challenging due to the complex interplay of multiple factors.

Several studies were carried out assessing the evolution of strength of stabilized clay samples with time (Chitambira (2004); Lorenzo et al., 2004; Kongsukprasert et al., 2007; Liu et al., 2013; Zhang et al., 2014; Yao et al., 2019; Mahedi et al., 2020; Nui et al., 2024). Zhang et al. (2014) investigated the long-term strength of cement-stabilized clays, incorporating temperature effects, by modifying the Chitambira evolution model to predict the UCS of cemented clays with curing duration. Their study demonstrated that higher curing temperatures accelerated the strength gain and increased the ultimate strength of the stabilized clay. Yao et al. (2019) modelled the strength gain of stabilized clay with time using a hyperbolic function, predicting both short-term and long-term responses. The UCS data were normalized over time with reference to the 7-day UCS or stiffness value. However, the study did not report the rate of tensile strength increase for clays stabilized with PBFC and OPC. Furthermore, the rationale for selecting the 7-day UCS/stiffness value as the normalization reference was not clearly addressed. In contrast, Nui et al. (2024) estimated the long-term strength of cemented clay using a modified Gompertz function that incorporated the maximum asymptote, inflection time, and growth rate. These results indicated a longer inflection time for samples stabilized with Portland blast-furnace slag cement (PBFC) compared with those stabilized with ordinary Portland cement (OPC). The main similarity among all the models for predicting the long-term strength or stiffness is existence of an asymptotic strength. These models assume a negligible improvement in the strength of stabilized clay samples once the curing period exceeds the asymptotic time. However, these models fail to explain the mechanism of enhancement in the asymptote region.

While significant amount of research has been carried out to assess and predict the long term strength of cemented clays through UCS, limited studies were carried out on assessing the evolution of tensile strength with time. Further, limited research has explored the probable long-term stabilization mechanisms for clays stabilized with different cementing agents. Recent study by Nui et al. (2024) proposed an alternative non-destructive test to assess the long-term properties of cemented clays through small strain stiffness, obtained from bender element test. However, these test setups require sophisticated instruments and present a challenge to execute, particularly in standard laboratory conditions. The present study aims to assess differences and similarities in the strength evolution of different clays stabilized with cement, and compare the evolution of tensile strength through BTS experiments, proposing a new measure of strength for cemented clay samples. Additionally, the novelty of this study lies in proposing a strength enhancement mechanism based on active and dormant bond development, aimed at reforming the current overly conservative design practices.

2 MATERIALS AND METHODS

2.1 *Materials*

To assess the performance of cement-stabilized clay, the present study utilized marine clay sourced from Ennore, Chennai, India. To investigate the influence of plasticity on the long-term performance, a second marine clay with higher plasticity was procured from Cochin, India. Bandaru et al. (2024) present the properties of Ennore marine clay (EMC) and Cochin marine clay (CMC), determined in accordance with ASTM standards. Based on the Unified Soil Classification System (USCS; ASTM D2487-11, 2018), EMC was classified as low-plastic clay (CL), while CMC was classified as high-plastic clay (CH). Both clays exhibited alkaline pore pH values, measuring 8.60 for EMC and 8.50 for CMC. The EMC was air-dried, pulverized, and sieved through a 2 mm sieve to remove shells and other foreign matter. Due to its high plasticity, CMC was wet-sieved through a 2 mm sieve for the same purpose. The processed clays were stored in airtight containers to prevent contamination. The chemical oxide composition of OPC shown in Bandaru et al. (2024) is considered for inducing artificial cementation in clay. The oxide composition of OPC is primarily composed of calcium oxide (CaO, 67%), and silica dioxide ($\mathrm{SiO_2}$, 15%), with trace amounts of ferric oxide ($\mathrm{Fe_2O_3}$, 6%).

Table 1. Physico-chemical properties of EMC, and CMC

Parameter	EMC	CMC	Units
Specific gravity	2.65	2.7	-
Liquid limit	45	103	%
Plastic limit	16	34	%
Pore pH	8.60	8.5	-
Sand content	33	23	%
Silt content	41	28	%
Clay content	26	49	%
Classification	CL	CH	-

Table 2. Oxide composition of OPC

Oxides	Composition (%)
$\mathrm{SiO_2}$	15.46
$\mathrm{Al_2O_3}$	4.87
$\mathrm{Fe_2O_3}$	6.59
CaO	66.74
$\mathrm{K_2O}$	0.79
$\mathrm{TiO_2}$	0.54
$\mathrm{SO_3}$	2.92

2.2 *Methodology*

Initially, the clay was oven-dried for 24-hours to remove the moisture present. The soil was then allowed to cool and remoulded at the target water content specified in Table 3 through a mechanical mixer for 20 minutes. The cement slurry with a water-to-cement ratio (w/c) of 0.6 was prepared and subsequently combined with the clay slurry. The cement–clay mixture was mechanically mixed for ten minutes to achieve homogeneity, as confirmed through visual inspection. Intermittent manual mixing was performed to prevent lump formation. The final cement–clay mix was placed into moulds for curing. After 24 hours, the specimens were demoulded, wrapped in cling film, and stored in a desiccator until testing.

The unconfined compressive strength (UCS) of the cemented clay was tested on UTM frame equipped with a 20 kN load cell. Cylindrical specimens of 50 mm diameter and 100 mm height were used for the UCS experiments. Three identical specimens, each having a diameter of 50 mm and a height of 100 mm were tested for unconfined compressive strength after a curing period of 7 days, 28 days, and 120 days to assess reproducibility. Compression experiments were carried out at a constant deformation rate of 0.625 mm/min as per ASTM D2166-06. The present study adopts BTS experiments to estimate the tensile strength of cemented clay samples. The BTS specimens, with dimensions 50 mm in diameter and 25 mm in thickness, were tested at a deformation rate of 0.625 mm/min, as per ASTM D3967-16. The average values obtained from the three UCS and BTS specimens were reported as the UCS and BTS of the respective sample. For microstructural studies, the samples were freeze-dried and stored in an air-dried container. The freeze-dried samples were sputter-coated with gold and subsequently imaged using scanning electron microscopy (SEM).

Table 3. Summary of EMC stabilization program

Mix	Clay type	Cementing agent	A_w (%)	w_r (LL)
E-O-1	EMC	OPC	5, 10, 15, 20	1.30
E-O-2	EMC	OPC	5, 10, 15, 20	1.10
C-O-1	CMC	OPC	10	1.10
C-O-2	CMC	OPC	10, 15, 20, 30	1.20
C-O-3	CMC	OPC	15	1.30

3 RESULTS

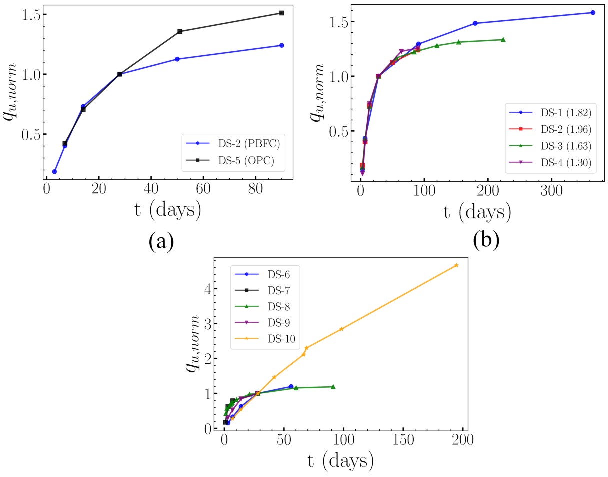
The section details the effect of various key influential properties such as remoulding water content, and clay plasticity on the evolution of compressive and tensile strength of cement-stabilized clays with time. The mechanical behaviour of the cemented clay samples was assessed through UCS and BTS tests, while the microstructure of the cemented clays was evaluated through SEM studies. Further, the effect of the influential parameters such as curing temperature, and binder type was collected from the literature, as the corresponding experiments were not performed in the present study due to scope and resource constraints. The results were compiled from previous studies reported by Zhang et al. (2014), Marzano et al. (2009), Porbaha et al. (2000), Clare and Pollard (1954), Yun et al. (2006), Impe and Flores (2006), and Bandaru et al. (2025), as shown in Table 4. From the literature, the effect of remoulding water content, curing temperature, and cement type were assessed through the results reported in DS-1 to DS-5 (Zhang et al., 2014) in Table 4. The current study evaluated the effect of cement dosage (5-20%), remoulding water content (1.0-1.3 LL), and clay plasticity (EMC, and CMC) on the evolution of the tensile strength of cement stabilized clay, shown in Table 3. The cement composition is in agreement with the average composition reported by Hewlett and Liska (2019).

Table 4. Database considered for evaluating the evolution of UCS with time

Dataset number	Clay type	Cementing agent	A_w (%)	w_r (LL)	Reference
DS-1	SMC	PBFC	14.4	1.82	Zhang et al. (2014)
DS-2	SMC	PBFC	13.7	1.96	
DS-3	SMC	PBFC	11.8	1.63	
DS-4	SMC	PBFC	10	1.30	
DS-5	SMC	OPC	11.8	1.96	
DS-6	AC	OPC	10	1.5	Marzano et al. (2009)
DS-7	YC	OPC	30	1.2	Porbaha et al. (2000)
DS-8	HC	OPC	15	-	Clare and Pollard (1954)
DS-9	DMC	OPC	-	3.0	Yun et al. (2006)
DS-10	AMC	PBFC	-	1.0	Impe and Flores (2006)
DS-11	EMC	OPC	5,10,15,20	1.2	Bandaru et al. (2025)

3.1 *Unconfined compressive strength*

The UCS is considered as a key indicator for assessing the strength enhancement resulting from cementation in clay samples (Kang et al., 2023). Figure 1 illustrates the variation in normalized UCS value with time for cement-stabilized clays. In these studies, the UCS values were normalized with respect to the 28-day strength of each respective sample. Additionally, a new term, "asymptote time" is introduced to denote the curing duration beyond which further strength gain become negligible. DS-1 to DS-5, from Table 4 studied on Singapore marine clays (SMC), stabilized with PBFC and OPC, while DS-6 to DS-10 were conducted on artificial clays (AC), Yokohama clay (YC), Hants clay (HC), Dongkwanyang marine clay (DMC), and Antwerp marine clay (AMC), stabilized at water content greater than liquid limit. From Figure 1(a), the asymptotic time for SMC stabilized with PBFC was significantly lower than that stabilized with OPC, indicating a slower rate of strength gain in OPC-stabilized samples compared to those stabilized with PBFC. For instance, clay stabilized with OPC exhibited a 51% increase in UCS relative to its 28-day strength, whereas clay stabilized with PBFC showed a 24% increase. From Figure 1(b), the influence of remoulding water content on the rate of strength gain in SMC was negligible, preventing any conclusive interpretation. From Figure 1(c) illustrates the rate of strength gain for different clays (DS-6 to DS-10) stabilized at varying water contents. Based on the above observations and Figure 1(c), clay type had a pronounced effect on the asymptotic time compared to the binder type and the remoulding water content. The asymptote time ranged from 28 to 50 days for PBFC-stabilized clay and extended to 90 days for PBFC-stabilized clay. For instance, in Figure 1(c), AMC upon stabilization with PBFC, the 200-day strength showed a 370% increase compared to the 28-day strength, indicating a significant effect of clay type on the asymptotic time.

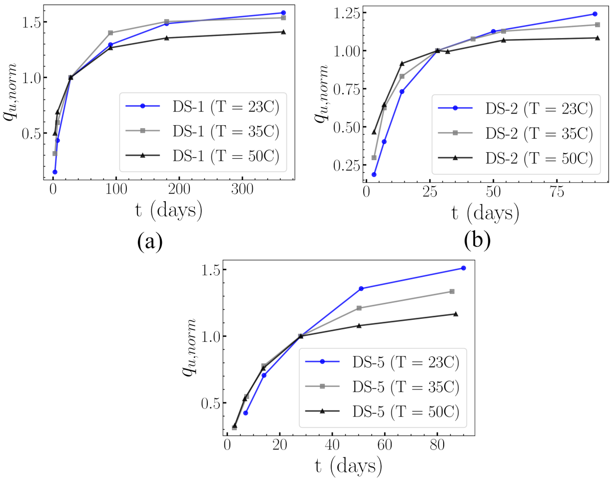


(a) (b)

(c)

Figure 1. Variation of normalized UCS value with time for different clays stabilized with cement, cured at $T = 20 \pm 3°$ C.

Figure 2 presents the combined effect of temperature, remoulding water content and binder type on the strength enhancement of stabilized SMC. Initial observations indicate that the influence of curing temperature on early-age strength development is substantially greater for SMC stabilized with PBFC than for those stabilized with OPC, as shown in Figure 2(b) and Figure 2(c) with PBFC stabilized sample attaining 50% of the 28 day strength in 3 days at 50°C as opposed to 18% when cured at 23°C. The time asymptote for OPC stabilized clay significantly decreased with increase in curing temperature, with time asymptote reaching to 50 days for sample cured at 50°C as opposed to 90 days, for samples cured at 23°C. However, significantly higher effect has been observed on the asymptote time for clay stabilized with PBFC. For instance, the asymptote time for the sample cured at 50°C was 14 days, whereas it ranged from 50 to 90 days for the sample cured at 23°C, indicating a substantial reduction with curing temperature.



(a) (b)

(c)

Figure 2. Effect of temperature on OPC and PBFC stabilized SMC

The combined effect of curing temperature and remoulding water content on the long-term strength evolution is shown in Figure 2(b) and Figure 2(c). The DS-1 sample was stabilized at relatively lower remoulding water content in comparison to DS-2. For DS-1, the asymptote time was least for samples cured at

35°C, and highest for samples cured at 23°C. However, for DS-2, the asymptote time was least for samples cured at 50°C, and highest for samples cured at 23°C. Moreover, the samples cured for 3 days attained significantly higher strength for samples stabilized at lower water content (DS1) as opposed to samples stabilized at higher water content (DS2)

However, certain low plastic clay exhibit a linear increase in strength (UCS) with curing period for significantly longer durations (t>120 days). Bandaru et al. (2025) reported the strength evolution for EMC at different cement dosages, stabilized at 1.20 LL, shown in Figure 3. A linear strength gain over time was observed for EMC stabilized with 5%, 10%, 15%, and 20% OPC. For instance, the UCS of the sample stabilized with 5% cement dosage cured for 120 days exhibited an average increase of 47% with respect to 28 days cured sample. However, the sample stabilized with 10, 15, and 20% cement dosage exhibited an average increase of 185%, 180%, and 162%, respectively. However, the 20% cemented clay samples stabilized at 1.30 LL exhibited a declining rate of strength gain with time, unlike those stabilized at 1.20 LL.

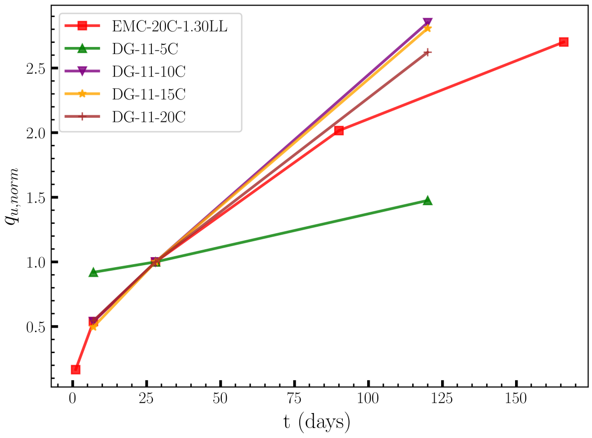


Figure 3. Effect of curing period on the normalized UCS of EMC stabilized with OPC

3.2 *Brazilian tensile strength*

The bond strength of the cemented clay samples was assessed through indirect tensile test or BTS test. Figure 4 and Figure 5 illustrates the variation in BTS value of EMC and CMC stabilized with different proportion of OPC. The EMC samples were stabilized at 1.10 and 1.30 LL, while the CMC was stabilized at 1.10, 1.20, and 1.30 LL, denoted as A, B and C in Figure 5, respectively. The EMC-stabilized samples exhibited markedly different behaviour depending on the remoulding water content. For example, the 20% cemented clay sample stabilized at 1.10 LL reached the asymptotic time within 90 days. A similar trend was observed in samples stabilized with 5% and 10% cement dosages at 1.10 LL. In contrast, samples stabilized at 1.30 LL exhibited a longer asymptotic time. This behaviour indicates that samples stabilized at lower remoulding water content exhibits faster bond development and strength stabilization. Moreover, the lower asymptotic time for samples stabilized at lower remoulding water content can be attributed to lower porosity in the system, as opposed to an increased porosity in samples stabilized at 1.30 LL. In contrast, samples stabilized at significantly higher remoulding water content exhibited an extended asymptotic time, likely due to slower hydration kinetics and delayed microstructural densification. However, the highly plastic CMC exhibited a pronounced effect on asymptote time with cement content as opposed to the low-plastic EMC.

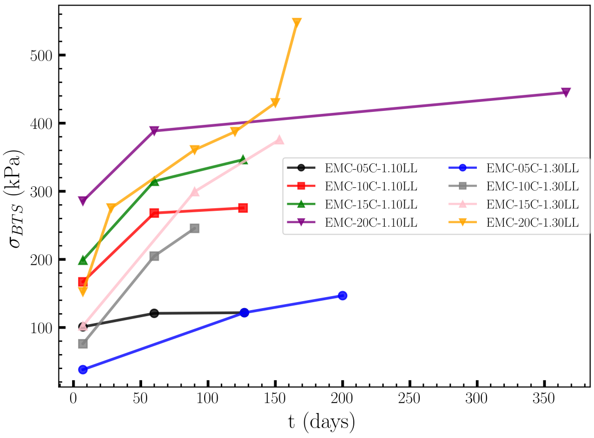


Figure 4. Variation of tensile strength of EMC with time for different cement dosages

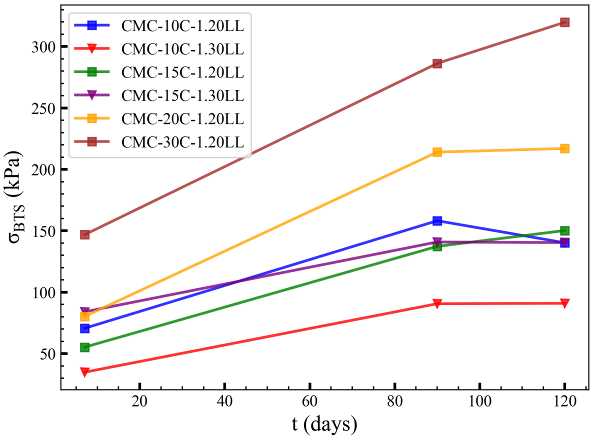
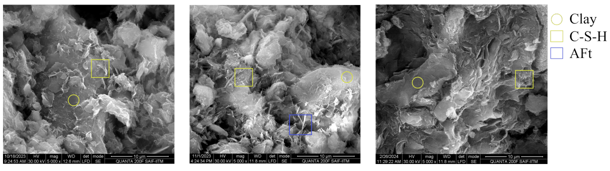


Figure 5. Variation of tensile strength of CMC with time for different cement dosages and remoulding water content

3.3 *Microstructure with time*

The microstructure of EMC, stabilized with OPC was evaluated at 7, 28, and 120 days, shown in Figure 6. The 7-day cured specimen exhibited significantly lower C-S-H gel (yellow box in Figure 6) and Ettringite needles formation (Aft, blue box in Figure 6), with significantly higher retention of clay fabric (yellow circle in Figure 6). However, the 28-day cured sample exhibited a substantial formation of ettringite needles along with C–S–H gel. By 120 days, the microstructure had become densely fused, with a significant reduction in pore volume.



(a) (b) (c)

Figure 6. Microstructure of EMC, stabilized with OPC, cured for (a) 7 days, (b) 28 days, and (c) 120 days

4 DISCUSSION

The UCS and BTS results indicate that strength enhancement in cement-stabilized clays can arise from densification or from the development of stronger interparticle bonds. Additionally, the clay plasticity as well as the binder type greatly influences the rate of strength enhancement with time for the cement stabilized clays. Bandaru et al. (2025) proposed two different types of bonds between the particles upon stabilization – Engaged bond, and dormant bond. In this study, the proposed bond types are employed to elucidate the stabilization mechanisms in samples subjected to long-term curing (t > 60 days). Figure 7 presents the proposed mechanism of bond enhancement in clays stabilized with a cementing agent. The initial increase in strength and the stiffness is attributed to bond formation between the particles as well as reduction in the pore space, as shown in “A” of Figure 7. Increase in curing period further enhances the bonds between the particles, with limited filling in pores, shown in “B”. The sample exhibits maximum enhancement in the bond between the particles in “C”, with further curing decreasing the pores between the soil particles. These bonds are load bearing in nature, thus are considered as active bonds or engaged bonds. The cementitious gel formed due to nucleation of cement particles at the pore space is not load bearing, and are considered as dormant bonds. The present theory suggests that active bond enhancement occurs up to the asymptotic time, after which further curing promotes the development of the dormant bonds. The proposed mechanism is in agreement with the microstructure observed in Figure 6 for 120 days cured 20% cemented EMC sample, with fused microstructure.

The sample exhibits active bond enhancement up to the asymptotic time, followed by dormant bond enhancement thereafter. The increased density and significantly reduced void ratio observed after the asymptotic time are attributed to dormant bond enhancement.

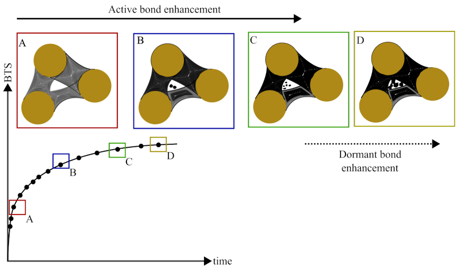


Figure 7. Proposed mechanism for bond enhancement in cement stabilized clays

5 CONCLUSIONS

The present study assessed the effect of soil plasticity, remoulding water content and the binder type on the long term response of cement stabilized clays. Additionally, the study introduced asymptotic time as an indicator to assess the long-term behaviour of cemented clays. Furthermore, the similarities and the differences between the evolution of tensile strength and compressive strength with time was evaluated. Finally, the study proposes a mechanism of long-term strength gain for samples exhibiting a higher asymptotic time in UCS than in BTS, attributing it to engaged and dormant bond enhancement. From the comprehensive mechanical characterization along with microstructural studies and from the literature, following conclusions were drawn:

1. The study highlights that the 7-day and 28-day strength is not a reliable benchmark for clays stabilized with cementing agents such as OPC, PBFC, PSC, and PPC. This leads to a significant underestimation of strength for stabilized samples, potentially resulting in cement wastage.
2. The effect of temperature on the asymptote time for clay stabilized with PBFC was significantly more pronounced in comparison to the clay stabilized with OPC. Additionally, curing temperature had a significantly greater influence on the early-age strength of SMC stabilized with PBFC than on those stabilized with OPC.
3. The evolution of bond strength is significantly influenced by the initial soil water content, as well as the cement dosage, along with the type of cement considered for stabilizing.
4. The effect of remoulding water content on asymptote time is more pronounced in low plastic clays compared to high plastic clays, whereas the effect of cement dosage is more pronounced in high plastic clays

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