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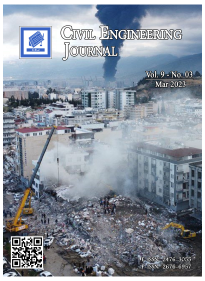

Investigating the Consolidation Behaviour of Cement-Bentonite Barrier Materials Containing PFA and GGBS

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Abstract

Cement-Bentonite (CB) barriers are expected to become a sustainable and reliable engineering solution. The deformation of CB is of interest to engineers to comprehend, particularly how CB responds to changes in loading during its construction and service life. The purpose of this study was to examine how samples of CB mixtures behaved during consolidation. This study investigated: (1) the influence of curing time and constituent materials on the consolidation properties of CB samples, (2) the volumetric change and the rate of volumetric change in response to a specific loading condition via consolidation tests. For this purpose, a laboratory consolidation test with a load range of 50 to 3200 kPa was carried out in accordance with BS 1377-7:1990 using the oedometer apparatus. This study discovered that the consolidation characteristics of CB samples are similar to those of overconsolidated soil. The CB sample became more resistant to consolidation under varying loads as curing progressed. The presence of more bentonite resulted in an increase in the recompression index. The inclusion of GGBS contributed to the consolidation characteristics of CB through the following mechanisms: (1) the significant decrease of the degree of consolidation with a curing period longer than 28 days, despite the slow strength development of the early-age curing; (2) the increase of the preconsolidation pressure; and the addition of GGBS was found to be more effective than the addition of more bentonite in increasing the preconsolidation pressure.

Keywords: Cement-Bentonite; Consolidation; Barrier Material; Clay; Geotechnical Engineering.

1. Introduction

Geotechnical engineering uses cement-bentonite (CB) mixtures very frequently in slurries for slurry trench cut-off walls, permeation grouting, jet grouting, for the soft piles in hard/soft pile systems, for boreholes, and for other sealing operations [1]. The problem of reducing the flow of water or other liquids from a dam, sanitary landfill, hazardous waste impoundment, industrial storage facility, or pumping plant has been dealt with and solved using a CB barrier, also known as a cut-off wall, which is one type of the slurry wall processes used to create underground barriers [2–4]. Design criteria for slurry walls used as structural elements may include hydraulic conductivity, strength, elastic modulus, erosion resistance, and other factors. However, the aforementioned requirements are insufficient if they are used to prevent contaminant transport in groundwater. Similar to the design of compacted clayey liners used in landfill construction, slurry walls should take hydraulic conductivity, adsorption, and hydrodynamic dispersion into consideration [5].

The use of CB mixture in cut-off trenches is expanding as a result of its clear advantages over other alternative methods. Many earlier researchers [4, 6, 7] have covered the topic of the benefits of selecting CB mixture in detail. The benefits are:

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- The backfill mix can be more uniform and consistent than soil-bentonite because the properties of cement can be managed. It has a higher potential to contain undesirable material, such as cobbles and clay lumps, due to the relatively unanticipated soil characteristics used in soil bentonite slurry walls. Therefore, this method is a respectable substitute for projects carried out on sites where the ground is covered in debris, trash, or other unusable materials.
- CB barriers can be more easily installed in places with limited access or space, like the tops of dikes or in between buildings, because of the absence of backfilling operations.
- The trenching through areas prone to failure is better suited for the CB slurry. Because it has a higher density than soil-bentonite slurry and typically sets in two to three hours, the risk of failure can be reduced.
- Less width was required for the CB trench than for the trench made of soil-bentonite.
- The CB wall sequence allows for flexible construction in sections to accommodate site limitations.

Despite its advantages, there are a few drawbacks to take into account before selecting CB mixture:

- Because cement is used as the backfill mixture, the cost of CB may be higher. However, the cost can be reduced by using substitutes for cement.
- The permeability of CB mixtures is typically 10^{-8} m/s, whereas soil-bentonite can reach 10^{-9} m/s [6, 8]. However, it is possible to reduce the permeability to 10^{-9} to 10^{-10} m/s by adding additives such as ground-granulated blast slag [7, 8].
- The set mix has a high moisture content, and both cement and bentonite are relatively susceptible to different types of degradation by water-borne contaminants [6]. Fly ash can be added to the mixture to reduce the degradation of the cement [7].

Numerous laboratory and in-situ investigations on the properties of slurry barrier mixtures had previously been conducted. Past studies examined the strength characteristics, compressibility and swelling behaviour, index properties, and permeability of commonly used slurry mixture constituents. Samuels [9] conducted research on the consolidation behavior of montmorillonite, the main mineral in bentonite. Other researchers [10, 11] conducted an experiment to investigate the compressibility behaviour of bentonite and concluded that the concentration and valence of the ions are significant factors in its compressibility behaviour, implying that chemical and physical reactions govern the change in compressibility characteristics. The finding was supported by studies on the one-dimensional compressibility behavior of bentonite at high pressures investigated by Tripathy & Schanz [12] and Baille et al. [13]. Robinson and Allam [14] further examined the impact of clay mineralogy on the coefficient of consolidation. In spite of this, it was difficult to draw a conclusion regarding the consolidation behaviour of CB barriers by comparing directly with the consolidation behaviour of its constituent material due to differences in the factors (such as chemical and physical factors) that govern their mechanical response to the loading; the majority of studies suggest that the cementing properties of CB play a substantial role in CB characteristics [15]. Furthermore, a direct comparison between untreated soil and CB is not appropriate because certain factors, such as the state of consolidation (e.g., normally consolidated, overly consolidated), the nature of the soil's fabric and bonding, and the condition and loading history [16], have been thoroughly researched and are well known for untreated soil, but this is not necessarily the case for CB [17].

Since both CB and cemented soils contain cementitious elements, a comparison between the two may be more apt. [18–24] studied the extent to which the incorporation of cementitious material into the soil improved the consolidation behaviour of clay. According to the majority of past studies, the addition of cement contributed by making the material become less consolidated and by leading to an increase in preconsolidation pressure [18, 21, 24]. Cai et al. [23] also claimed that the temperature at which the cement was cured and the method by which it was cured could contribute to an improvement in the compressibility characteristic of cemented soil. Despite these findings, it is important to point out that the primary distinction between CB and cemented soils lies in the fact that CB is produced from bentonite slurry, which indicates that it has a higher moisture content, and it contains a greater proportion of cementitious materials than the cemented soil, which renders the comparison a little slightly problematic. Additionally, the predominance of montmorillonite in bentonite, which is known for its swelling property, further complicates the comparison. The difference in the chemical reaction that occurs between the constituent materials in CB and cemented soils must also be taken into consideration. Due to these factors, this emphasizes the importance of conducting further investigation on the manner in which CB materials react when subjected to consolidation.

Considering its constituent materials, the closest comparison that can be made to CB is with other types of barrier materials. There have been some findings from the investigation into the properties of soil-bentonite or soil-CB mixtures. The behavior of the soil-bentonite and CB barriers can potentially be compared using the results of these earlier studies. Fan et al. [25] suggested that, to date, only a very few past studies have systematically examined the compressibility and hydraulic conductivity of soil bentonite. Baxter et al. [26] and Fan et al. [27] assessed the strength and 1-D compressibility characteristics of soil-bentonite mixtures; both suggested that the clay fabrics have a significant role in the characteristics. Ryan and Day [28], Evans [29], Daniel & Choi [30], and Filz et al. [31] evaluated the permeability and strength properties of soil-CB and soil-bentonite slurry walls toward curing time. Investigations into the swell and compressibility behavior of bentonite mixtures [32] and sand bentonite mixtures [33] had been conducted. Mishra et al. [34] had also conducted a study on the impact of bentonite on the consolidation behavior of soil bentonite mixtures. These past studies attributed cementation bonds as the factors contributing to the improvement in the consolidation characteristics of the material, establishing a relationship between cementation and consolidation behaviour. In past studies, however, the response of soil bentonite and soil CB to more variable loading regimes has not been adequately investigated, leaving a gap in the research. In addition, Opdyke and Evans [35] suggested that the mechanical strength of CB is significantly greater than that of soil-bentonite and soil-CB, implying that these types of barriers cannot be compared fairly to CB.

The investigation on the compressibility of CB is still very limited. Royal et al. [36, 37] looked into CB slurry samples that contained PFA in the UCS, triaxial, and consolidation apparatus. Despite publishing a study that covered more topics related to CB slurry systems [1], the issue of consolidation behavior was left out. In an effort to mitigate the substantial environmental threat posed by cement, researchers are attempting to reduce the amount of cement used while lowering construction costs by repurposing waste materials [38]. The use of byproducts of the steelmaking industry, such as slag, as a constituent material and partially replacing cement in CB barrier construction is one of the most common and recommended alternatives [39, 40]. Opdyke and Evans [35] performed a consolidation test on CB slurry samples that contained slag, but they did not investigate a comparison with CB that did not contain slag. Liu et al. [41] assessed the impact of a cement and bentonite mixture on the consolidation behavior of soft estuarine soils. Ding et al. [42] analyzed factors affecting the performance of CB walls. The role and effect of varying the bentonite and slag in the CB barriers and how they affect the consolidation behaviour of the material have not been thoroughly explored in prior research. In addition, it is necessary to investigate how the duration of curing impacts the consolidation behaviour of CB.

In spite of the widespread use of CB in geotechnical and geoenvironmental applications, the materials used for slurry walls and barriers continue to degrade in performance when subjected to mechanical, chemical, and environmental stresses [40]; causing concern over their serviceability and reliability. The failure of the CB barrier has been the primary source of concern for the engineers, specifically in relation to the loading and how it varies throughout the service life of the CB barrier [17, 43]. Due to the fact that settlement may take place after the construction of CB barriers, it is extremely important to evaluate the consolidation behaviour of these barriers. The compressibility of the mixture slurry is vital when building a barrier since it should result in a rigid structure with little settlement [6, 29, 44]. The investigation into the consolidation behaviour of CB material is still limited at the current state, as was previously elucidated, because it is still poorly understood how curing and changing mix proportions affect its performance. In light of the fact that comparing the consolidation behaviour of CB to that of other geomaterials is thought to be problematic, the purpose of this study was to investigate how different CB mixtures behaved when being consolidated. Due to constraints in retrieving in-situ CB samples from the site and conducting the in-situ consolidation test (the majority of previous studies isolated their studies on the laboratory experimentation using 1-D consolidation apparatus), the primary objective of this study was to investigate the behaviour of laboratory-cast samples of CB mixture during consolidation under different loading conditions. This study specifically investigated the influence of curing time, bentonite content, and cement replacement materials on the consolidation properties of CB barrier samples, as well as how the volumetric change and the rate of volumetric change of the CB material vary in response to a specific loading.

2. Literature Review

The performance of the CB mixture may be determined by the basic properties of cement and bentonite. The final qualities of CB are a function of the initial mix proportions, curing time, soil conditions, and sampling and testing procedures, according to Ryan & Day [6]. In the UK, there is not much difference in the types of materials used for slurry trench cut-off walls. According to Garvin & Hayles [45], the following materials have frequently been specified and used:

- Bentonite, normally sodium exchanged, described as CE (civil engineering) grade;
- Portland cement (PC);
- Materials used to partially replace PCs; they primarily include ground granulated blast-furnace slag (GGBS), but have also included pulverized fuel ash (PFA) and micro silica;
- Admixtures, these include set retarders and dispersants.

2.1. Bentonite

Bentonite is a type of clay mostly made up of montmorillonite, dioctahedral smectite. The classification of calcium or sodium bentonite results from the exchangeable cations of calcium, sodium, and, to a lesser extent, aluminum. The most popular type of bentonite used in the UK is sodium-exchange bentonite, also known as sodium-activated bentonite. This calcium bentonite has been treated with sodium carbonate. Anisometric particles form a linked, porous network in the microstructure of hydrated bentonite suspensions, contributing to their high sorptive capacity [45].

The primary mineral in bentonite, montmorillonite clay, exhibits compressibility behavior, and Samuels [9] assessed this behavior. It was discovered that applying a small pressure to sodium-based natural montmorillonite causes a significant volume reduction. Consolidation was found to begin at a slow rate, especially for the sodium variety, and to speed up over time. The rate of consolidation initially decreases with increasing loads on montmorillonite, but after a short while, the pressure increase has very little impact on the rate.

Due to its fineness and high silica and alumina content, sodium bentonite is regarded as a natural pozzolan that can enhance the mechanical properties of cemented materials. The increased reactivity of sodium bentonite to calcium hydroxide, which is liberated during cement hydrolysis, results in the formation of pozzolanic cementation bonds. Such bond formation has a positive impact because it results in an improved microstructure, tighter pores, and increased strength [46–48].

2.2. Portland Cement

Portland cement is made of fine powder that is created by grinding Portland cement clinker, which is created by heating materials in a kiln to create Portland cement clinker. With more time to cure, cement hydration products like concrete become more durable. If it is fully moist-cured as opposed to being allowed to dry in the air, the strength is significantly higher [49].

2.3. Cement Replacement Materials

Energy use and carbon dioxide emissions can be significantly reduced by using cement substitutes with less of an impact on the environment. GGBS is the most effective substitute for Portland cement. Up to 93% less carbon dioxide may be released into the atmosphere and 74% less energy may be used to produce cement when GGBS is used. Because GGBS can be produced without the need for mineral extraction, using it protects natural resources [50].

Granulated blast-furnace slag is a by-product produced during the production of pig iron, and the quantities of slag and iron produced are of similar order [51]. Because GGBS hardens very slowly, Portland cement is required to activate it before it is used in concrete. When the GGBS proportion is 70%, the strength gained after 7 days of curing is typically in the range of 40 to 50% of the strength gained after 28 days, and a further strength increase of 15 to 30% is obtained after 28 to 90 days of curing [52].

Fly ash, also referred to as pulverized fuel ash (PFA), is the by-product of burning pulverized coal in coal-fired power plants. Mixtures made of fly ash and Portland cement often hydrate more slowly than similar mixes made of Portland cement alone, but they may be more durable [53].

2.4. Cement-Bentonite

The hydromechanical behaviour of CB barriers varies with time, with their hydromechanical properties improving as the barriers cured and hardened for longer. This improvement is generally associated with a decrease in permeability and an increase in mechanical strength [54]. In addition, the proportion of constituent materials plays a crucial role in the overall performance of CB. For the CB barrier, there is no mandatory standard for the proportion of cement, bentonite, and water in the mixture. Nevertheless, the optimal ratio of the CB mixture has been thoroughly established through previous studies.

According to Table 1, bentonite makes up less than 6% of the slurry mixture on average, while cement makes up between 15% and 25% of the mixture. Most of the time, water makes up between 70 and 80 percent of the mixture. The fact that cement makes up a higher percentage of the mixture than bentonite suggests that cementitious material has a greater impact on the final properties of CB samples. These percentages can serve as a crucial point of reference when determining the ideal CB slurry mix design proportion.

Table 1. Typical Mixes of Cement Bentonite

Material	Jefferis [1]	Royal et al. [36]	Andromalos & Fisher [8]	Ryan & Day [6]
Bentonite	2-5 %	3 %	4 – 6%	3 – 6 %
Cement	16 – 25 %	16 %	12 – 20 %	16 – 35 %
Water	71 – 82 %	81 %	75 – 84 %	59 – 81 %

According to Garvin & Hayles [45], bentonite content above 3.2% significantly reduces permeability, and above 4.7% the slurry thickens and becomes challenging to mix and pump (the percentage is based on the assumption that the weight of water and cement takes up to 1200 kg). Therefore, it is crucial to choose the CB mixture carefully to guarantee that the sample will perform as expected.

The performance of the CB barrier is significantly influenced by the mixing process. According to Jefferis [1], the mixing process, which includes the type of mixer (mix head, rotational speed, etc.), mixing procedure (including mixing time), and order of component additions, can have an impact on the properties of CB materials. In contrast to low shear mixes, high shear mixing frequently results in materials with a finer pore structure and lower permeability. Therefore, a consistent mixing process is crucial to ensuring the consistent performance of the constructed CB barriers. The samples produced by mixing bentonite and cement simultaneously will differ significantly from those made with pre-hydrated bentonite [1].

3. Research Methodology

The majority of the study that was completed involved lab-based experiments. For the purposes of this study, a one-dimensional consolidation test using a standard oedometer apparatus was undertaken. The standard test procedure used to conduct consolidation tests is BS 1377-7:1990. The experimentation stages of this study can be broadly divided into three phases: sample preparation, testing, and result analysis.

3.1. Sample Preparation

3.1.1. Sample Specification

3.1.1.1. Bentonite

Berkbent™ 163 Bentonite was used in the CB mixture (Figure 1). Berkbent 163 is a free-flowing powder of premium grade high-quality sodium carbonate activated Bentonite. The amount of weight that is retained on 150 microns after a dry sieve is 5% [55].

(a) (b)

Figure 1. (a) Cement (b) Bentonite used for the creation of cement-bentonite samples

3.1.1.2. Cement

Rugby® CEM II/B-V cement was used to create the CB samples (Figure 1). Table 2 provides information on the composition of the cement used (British Standard EN 197-1: 2011) [56].

Table 2. Composition of CEM II/B-V Type

Constituents	Percentage
Clinker	65 – 79 %
Fly Ash (Siliceous)	21 – 35 %
Other minor constituents	0 – 5 %

Portland cement clinker is a hydraulic material that must contain at least two-thirds by mass of calcium silicates (3CaO SiO_2 and 2CaO SiO_2), with the remaining portion made up of other compounds and phases of clinker that contain iron and aluminum. Siliceous fly ash is a fine powder made up of pozzolanic particles that are primarily spherical in shape. Aluminium oxide (Al_2O_3) and reactive silicon dioxide (SiO_2) make up the majority of it. The remaining material includes other compounds and iron oxide (Fe_2O_3).

3.1.1.3. Ground Granulated Blastfurnace Slag (GGBS)

The typical chemical composition of GGBS is CaO (40%), SiO_2 (35%), Al_2O_3 (13%), and MgO (8%) [52] and sourced from Hansen Aggregates.

3.1.2. Mixture Proportion

For the CB samples tested during the laboratory test, there were three different types of mixture proportions prepared (Table 3). Based on the mix proportion used in the research conducted by Royal et al. [36], the initial proportion (Type 1) of 1000 gr water, 200 gr cement, and 40 gr bentonite was selected. Type 3 sample, which replaced 80% of the cement content with GGBS, was produced to analyze the effect of replacement on the sample's consolidation behavior. Type 2 sample mixture proportion was chosen to observe the change in CB samples consolidation behavior with an increase in bentonite content. The choice of the 80% replacement was in accordance with the recommendation of Jefferis [1].

Table 3. Water, bentonite, and cementitious material proportions in the sample mixture

Sample	Water (gr)	Bentonite (gr)	Cement (gr)	GGBS (gr)
Type 1	1000	40	200	-
Type 2	1000	55	200	-
Type 3	1000	40	40	160

3.1.3. Mixing Procedure

The methodology used in this study is based on Garvin & Hayles [45] and Royal et al. [36]. The following are the steps of the procedure:

- Using a commercial food mixer, the dry bentonite and all the water were blended for 30 minutes. Because it could affect the characteristics of CB samples, the mixing speed was regulated [1].
- At room temperature (20±5ºC), the bentonite slurry was allowed to hydrate for 24±1 hours.
- Replacement material (GGBS) was mixed with Portland Cement. To ensure the consistency and homogeneity of CB samples, it is strongly advised to blend the dry replacement material with Portland cement prior to mixing it with bentonite slurry. The visual differences between the CB sample with GGBS that was blended with Portland cement first and the sample with replacement material that was not blended with Portland cement are shown in Figure 2.
- The hydrated bentonite was mixed with the dry cementitious material. It is advised to mix for an additional 1-2 minutes to produce a more homogeneous sample even though the mixing time of 5 minutes is sufficient.
- CB fresh samples were poured into the molds, which were later sealed with plastic covers. To minimize air entrainment during the pouring process, the decanted slurry was placed on a vibrating table for 10 to 15 minutes.

(a) (b)

Figure 2. Portland cement was either a) not blended previously with GGBS and b) blended with GGBS first

3.1.4. Curing Procedure

Prior to starting the consolidation test, the samples were extruded and stored in laboratory-purified water after curing for at least 7 days inside the molds (as seen in Figure 3). The samples were cured in a cold room that maintained a temperature of 5°. The curing times were selected at 7, 14, 28, and 60 days. This choice was based on the curing times that were selected in previous studies [35, 36].

Figure 3. The curing of CB samples

3.1.5. Sample Casting

The samples should be carefully sawed to the desired height (which is advised to be slightly higher than the height of the ring) before being placed inside the metal rings for the consolidation test. After being inserted into the rings, the excess of the sample height was cut down to 19.1 mm, which is the height of the metal ring. The surface should be flat and smooth as seen in Figure 4.

(a) (b)

(c) (d)

Figure 4. (a) Cutting tools (b) Samples containing cement with PFA and (c) containing GGBS after they were trimmed (d) Sample was damaged during the cutting

3.1.6. Sample Testing

Approximately 29 samples were tested in total during the laboratory testing. The standard test procedure used to conduct the consolidation test is BS 1377-7:1990 [57] using Oedometer Apparatus (Figure 5-a). Figure 6 illustrated the flowchart of the study undertaken.

(a) (b)

Figure 5. (a) Oedometer Apparatus (b) Sample was taken out from the metal ring

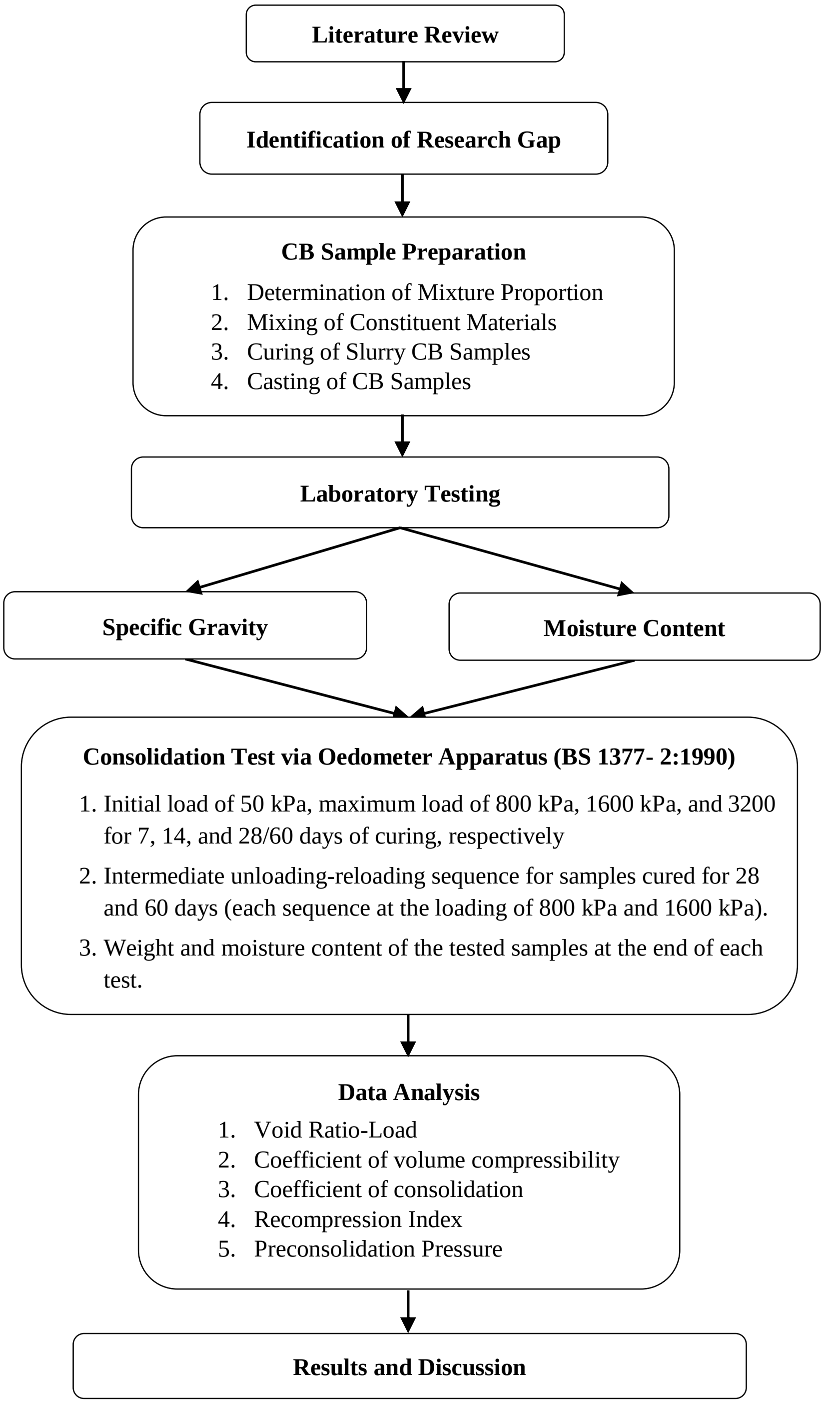


Figure 6. Flowchart of the research methodology

Prior to conducting the consolidation test, it is crucial to determine the initial moisture content and specific gravity of the samples, as this information is necessary for estimating the initial void ratio. Multiple samples were tested to determine the most precise range of values for moisture and specific gravity (BS 1377-2:1990) [58].

The loading schedule includes a load increment ratio of 1, which is obtained by roughly doubling the sample's total axial stress. The loading schedule and curing time of the samples are shown in Table 4. The standard load increment duration of 24 hours was selected. The axial deformation was recorded with time intervals of approximately 0.1, 0.25, 1, 2, 4, 8, 15, and 30 minutes, and 1, 2, 4, and 24 hours.

Table 4. Loading Schedule

Curing Time (day)	Sample Type	Applied Load (kPa)	
		Initial	Maximum
7	1, 2, and 3	50	800
14	1 and 2	50	800
14	3	50	1600
28	1, 2, and 3	50	3200
60	1, 2, and 3	50	3200

After applying the maximum load, the applied load was gradually decreased every 24 hours or earlier if possible until the sample was not under any load. For samples that had been in curing for 28 and 60 days, an intermediate unloading-reloading sequence was carried out. The samples were loaded up to 800 kPa before the first intermediate unloading sequence was started. Following the application of the 1600 kPa load, another sequence was carried out. The sample weight was determined after the loading phase ended, and the sample was removed from the metal ring (as seen in Figure 5). The sample was then placed in an oven set at 105°C ± 5°C for about 24 hours, and its weight was once again measured to determine the post-test moisture content.

There were mainly two graphs that can be produced from each sample: void ratio versus log-effective applied load and root time versus deformation. The coefficient of volume compressibility (m_v) is calculated using equations below (Equations 1 and 2):

$$m_v = \frac{1}{1+e_0}\left(\frac{e_0-e_1}{\sigma'_1-\sigma'_0}\right) \tag{1}$$

$$m_v = \frac{1}{H_0}\left(\frac{H_0-H_1}{\sigma'_1-\sigma'_0}\right) \tag{2}$$

where σ_0 is initial load, σ_1 is final load, e_0 is initial void ratio, H_0 is initial height of specimen, and e_1 and H_1 are void ratio and height of specimen after the consolidation test. The value of void ratio can also be calculated using below Equation 3:

$$\frac{\Delta e}{1+e_0} = \frac{\Delta H}{H_0} \tag{3}$$

coefficient of consolidation (c_v) can be obtained from the root time method. The equation used to calculate c_v is as follows (Equation 4):

$$c_v = \frac{T_v H^2}{t} \tag{4}$$

where the value of T_v corresponding to U_v = 90% is 0.848, H is average thickness of specimen for each pressure increment and t is time.

The recompression index (c_s), or rebound, was calculated using equations below (Equation 5):

$$c_s = \frac{e_0-e_1}{\log \sigma'_1/\sigma'_0} \tag{5}$$

e_0 and σ_0 represent void ratio and applied load before the unloading and e_1 and σ_1 are void ratio and applied load at point before the loading is applied.

Pre-consolidation pressure was obtained using method proposed by Casagrande [59].

4. Results and Discussion

4.1. Specific Gravity

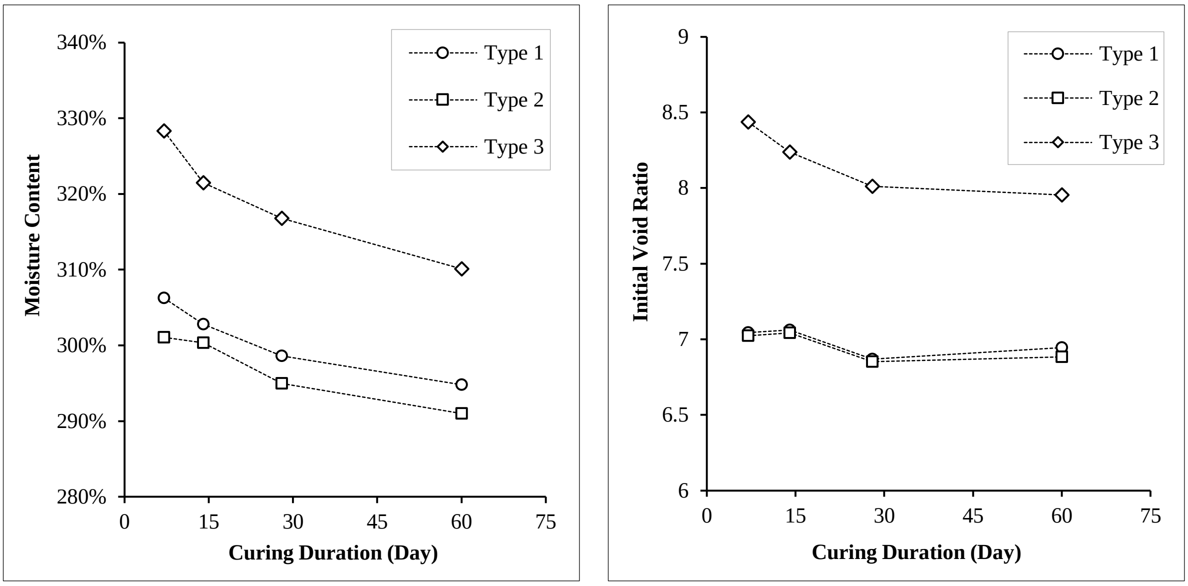
For bentonite, cement with PFA, GGBS, and all types of CB samples, specific gravity tests were performed. Table 5 provides a summary of the testing.

Table 5. Specific gravity

Sample	Specific Gravity
Bentonite	2.6
Cement	2.2
GGBS	2.9
Type 1	2.4
Type 2	2.4
Type 3	2.6

4.2. Moisture Content

It is necessary to perform a moisture content test in order to determine the initial void ratio of the sample tested in the oedometer. Figure 7-a demonstrates that the initial moisture content of type 2 samples was marginally less than that of type 1 samples, indicating that the addition of bentonite content caused the moisture content of the CB sample to decrease. Increased moisture content was the result of replacing cement with GGBS (80%). For all types of samples, there was a consistent trend in the change of moisture content; it dropped as the curing time increased. As the percentage of solids (bentonite and cementitious materials) only makes up about 20% of the entire sample mixture, large values of the void ratio, which are indicative of material having a very slow solids content, were expected (as seen in Figure 7-b).



(a) (b)

Figure 7. (a) Average initial moisture content and (b) void ratio with curing time

4.3. Consolidation and Swelling

4.3.1. Type 1

Relationships between void ratio and effectiveness for type 1 samples are shown in Figure 8-a. The virgin compression lines can be seen to be becoming flatter as the curing time increases. This indicated that there was an increase in the strength of sample fabric, particularly for cementitious products, as calcium silicate hydrate hardens over time and gains a greater resistance to particle breakdown. These findings agreed with previous research [54], which suggested that CB mechanical strength is related to the length of curing (as cement requires time to hydrate), including its resistance to compression. The overall compression experienced by the samples decreased as they cured longer (particularly those cured for 28 and 60 days) which is represented by smaller drops from the initial void ratio).

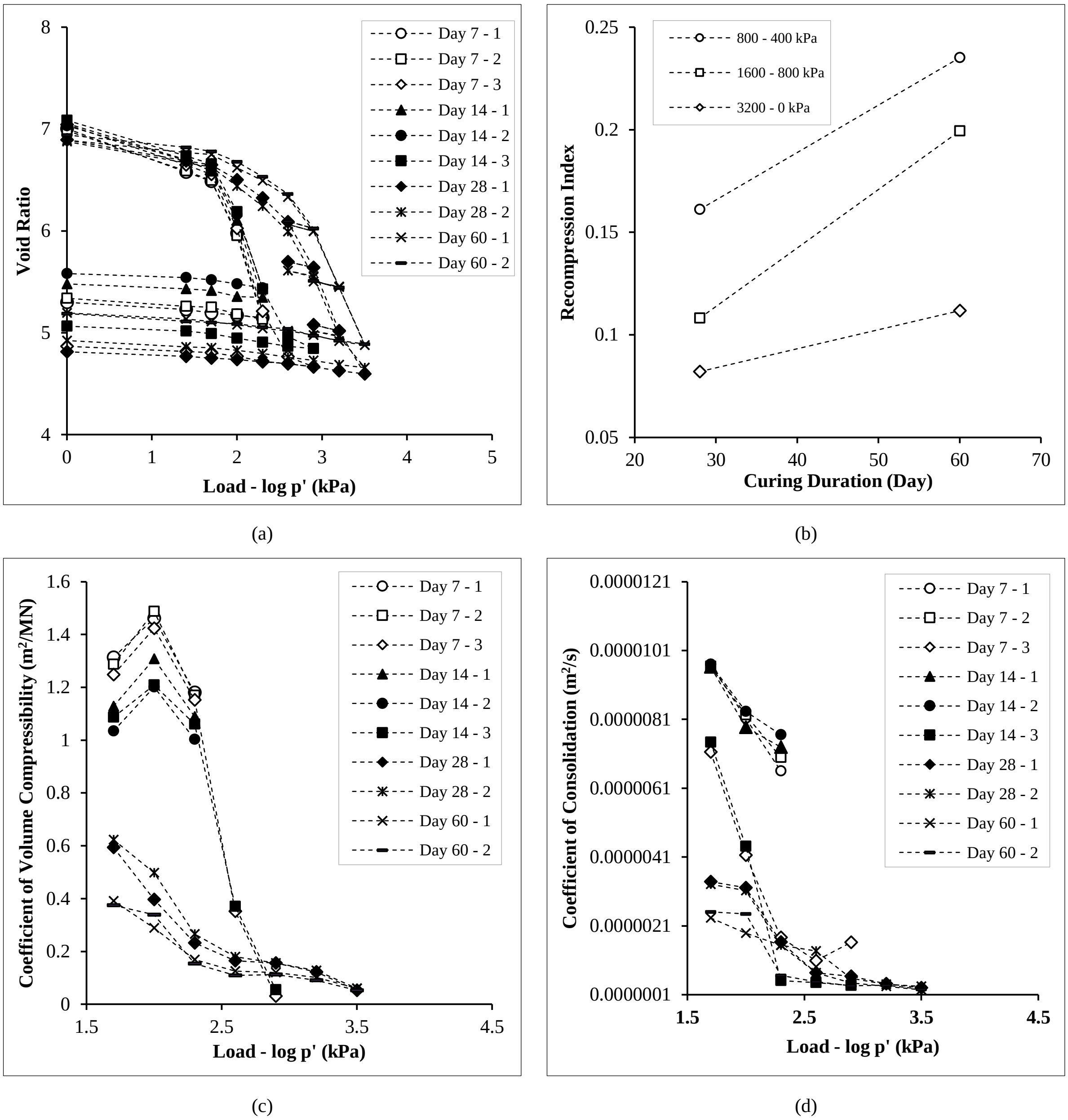


Figure 8. Type 1 (a) Void ratio-effective load (b) Recompression index-curing time (c) mv - effective load, and (d) c_v - effective load

With regard to the recompression index (as seen in Figure 8-b) for both intermediate unloading stages (800-400 kPa and 1600-800 kPa) and the final unloading stage (3200 to 0 kPa), the recompression index was primarily correlated with the stress level experienced by CB samples. In the intermediate stage, following the application of 800 kPa and 1600 kPa, an unloading-reloading sequence was carried out on samples that had been cured for 28 and 60 days. The recompression indexes at this stage decrease as the load increases. This was anticipated due to the fact that samples subjected to greater loading exhibited much greater reductions in void volumes, more severe destruction of interparticle bonds, and a greater particle packing arrangement, resulting in denser samples and a reduced rebound capacity. It can also be observed that there was an increase in the recompression index as a result of curing, which corresponds to an increase in the rebound capacity of the CB samples as the curing period lengthens. This suggested that the cementation bonds that strengthen over time contributed to the increased capacity of the material to recover from compression to some degree.

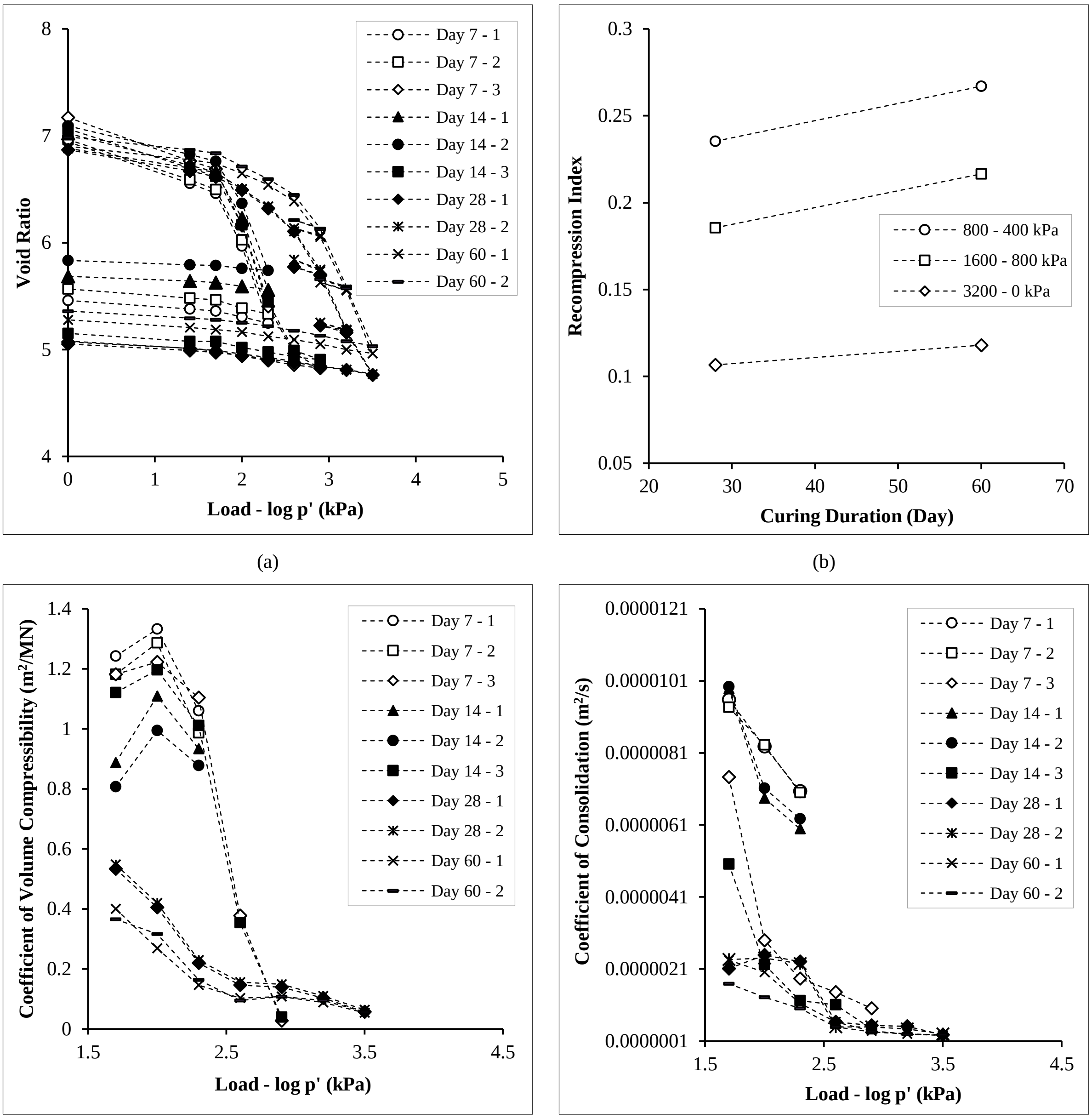
When the load that was applied to the samples was greater than the preconsolidation pressure, which is the point at which the compression lines became steeper, a significant volumetric change in response to the load was observed for type 1 samples. This concurred with the claim from Manassero et al. [60] and Soga et al. [61] that the significant restructuring of CB fabric occurs when the load applied exceeds the preconsolidation pressure, despite the absence of loading history for CB. The values of m_v obtained range from 1.48 to 0.032 m^2/MN (as seen in Figure 8-c). Sensitive clay typically has a m_v value greater than 1 m^2/MN. Soft normally consolidated clay and firm overconsolidated clay, respectively, are typically associated with m_v values between 0.1 and 0.3 m^2/MN and 0.3-1 m^2/MN, respectively.

According to Barnes [62], overconsolidated clay that is stiff to very stiff has a mv value lower than 0.1 m^2/MN. These values indicated that, depending on the curing time, the CB samples exhibited a range of volumetric changes in response to load that can be compared to normally consolidated to overconsolidated clay.

The correlation between c_v and the effective load for type 1 samples is shown in Figure 8-d. There was little difference in the value of c_v between samples that were cured for 7 and 14 days. The trend is similar, though, in that it declined as the applied load increased. With an increase in applied load, the c_v decreased more steadily in samples that have been cured for 28 and 60 days. For samples cured for 28 days as opposed to 60 days, the value of c_v was marginally higher.

4.3.2. Type 2

The void ratio-effective relationships of type 2 samples were very similar to those of type 1 samples (Figure 9-a). Similar to type 1 samples, virgin compression lines become flatter with extended curing times, and this change was particularly noticeable after 28 days of curing.



(a) (b)

(c) (d)

Figure 9. Type 2 (a) Void ratio-effective load (b) Recompression index-curing time (c) mv - effective load and (d) cv - effective load

In general, type 2 samples had recompression indexes that were higher than type 1 samples (Figure 9-b), and this increase was due to the inclusion of bentonite in the CB samples. Thus, it can be inferred that the presence of bentonite increases the capacity of the CB to recover from the restructuring of fabric caused by the consolidation.

Figure 9-c shows the relationship between m_v and effective load for type 2 samples. The values of value of mv obtained were ranging from 1.33-0.035 m^2/MN. The characteristics were fairly comparable to those type 1 samples.

The correlation between c_v and the effective load for type 2 samples is shown in Figure 9-d. The value of c_v did not significantly differ between samples that were cured for 7 and 14 days. However, the trend is similar in that it dropped as the applied load increased. There was a more consistent decline in c_v with increasing applied load for samples that have been in curing for 28 and 60 days. Samples cured for 28 days had a slightly higher c_v value that those cured for 60 days

4.3.3. Type 3

The void ratio-effective relationship for type 3 samples is shown in Figure 10-a. When samples were cured for 7 days to 28 days, it was visible that the virgin compression lines become steeper, and when samples were cured for 60 days, they become flatter.

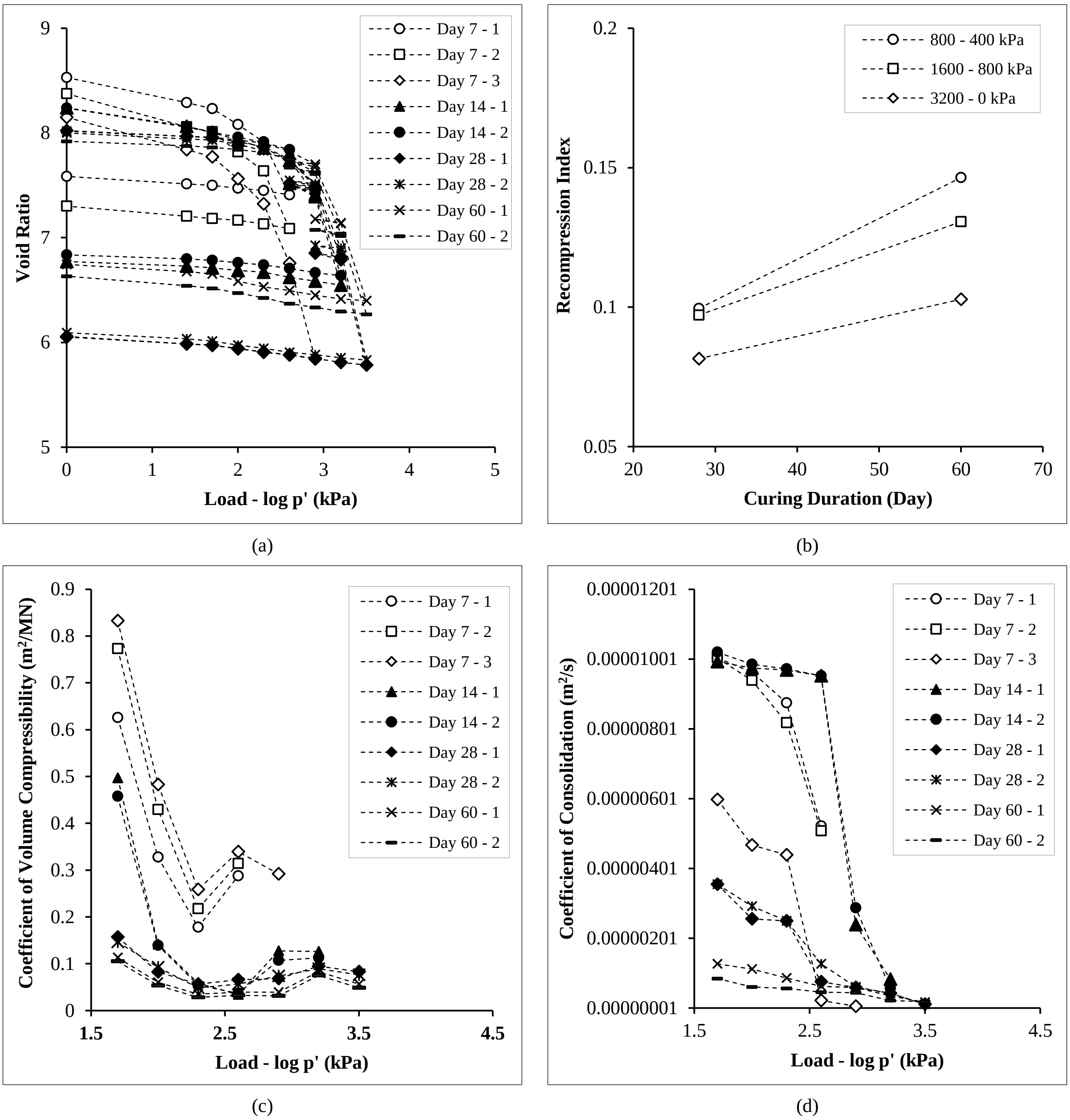


Figure 10. Type 3 (a) Void ratio-effective load (b) Recompression index-curing time (c) mv - effective load and (d) cv - effective load

The consolidation of type 3 samples was comparably greater after they have been cured for more than 14 days when compared to type 1 and type 2 samples that do not contain GGBS. This phenomenon can be explained by the fact that concrete made with GGBS gains strength more steadily than concrete made with Portland cement. While GGBS concrete will have greater long-term strength for the same 28-day strength, it will have lower strength at younger ages. Typically, Portland cement concrete will reach about 75% of its 28-day strength at seven days, and will only slightly increase by 5% to 10% between 28 and 90 days. In contrast, the strength at seven days for concrete with a 70% GGBS would typically be 40 to 50% of the strength at 28 days, with a further strength increase of 15 to 30% from 28 to 90 days. Very little early-strength gain could result from GGBS proportions of 80–95% [52]. The CB sample fabric must take more time to reach its peak strength, especially for cementitious products containing GGBS, which can make up to 67% of the solids. Early-formed particle grains and bonds did not undergo as rapid a hardening as samples made with cement that contained PFA. Because of the increased rate of interparticle bond breakdown and quick rearrangement of particle packing, the compression for samples cured from 7 to 28 days increased. The decrease in compression for samples that have been in curing for 28 to 60 days was a sign that the fabric's strength had increased, increasing the sample's resistance to particle breakdown and resulting in a less compressive sample.

As sample strength improves over time, it was also expected that the recompression indexes increased as the curing time increased (Figure 10-b). The compression indexes for type 3 samples were found to be lower than the other types, implying that the addition of GGBS reduced the capacity of CB fabric to recover from the consolidation process. This response to unloading could be attributed to the particle arrangement following the restructuring, which resulted in a denser packing of the particle structure, contributing to a drop in recovery capacity.

Figure 10-c shows the relationship between m_v and effective load for type 3 samples. The obtained values of m_v range from 0.84 to 0.03 m^2/MN, slightly lower than type 1 and 2 samples. The values correspond to firm overconsolidated clay and consolidated clay, respectively. Overconsolidated clay that is stiff to very stiff typically has a m_v value below 0.1 m^2/MN [62].

The correlation between c_v and effective load for type 3 samples is shown in Figure 10-d. The value of c_v for samples that had been in curing for 28 and 60 days decreased steadily as the load increased. For samples that had been cured for 60 days, the c_v decreased more gradually. Similar to type 1 and 2 samples, for samples cured for 28 days as opposed to 60 days, the value of c_v was comparatively higher.

4.3.4. Comparison of Consolidation Behaviour to Past Studies

Figure 11 summarised the comparison of the consolidation curve from the present study (samples cured for 28 days) and relevant past studies [15, 20, 25, 35]. CB samples evidently demonstrated a slightly different compression trend than SB and cemented soils. CB samples experienced significant compression only after the preconsolidation pressure was exceeded, as discussed in greater detail in the following section. [15] argued that the presence of cement influences the CB response to consolidation, particularly during virgin loading and unloading. Although it was evident that the presence of GGBS improves the CB response to consolidation, the impact of GGBS in varying proportions remains to be investigated.

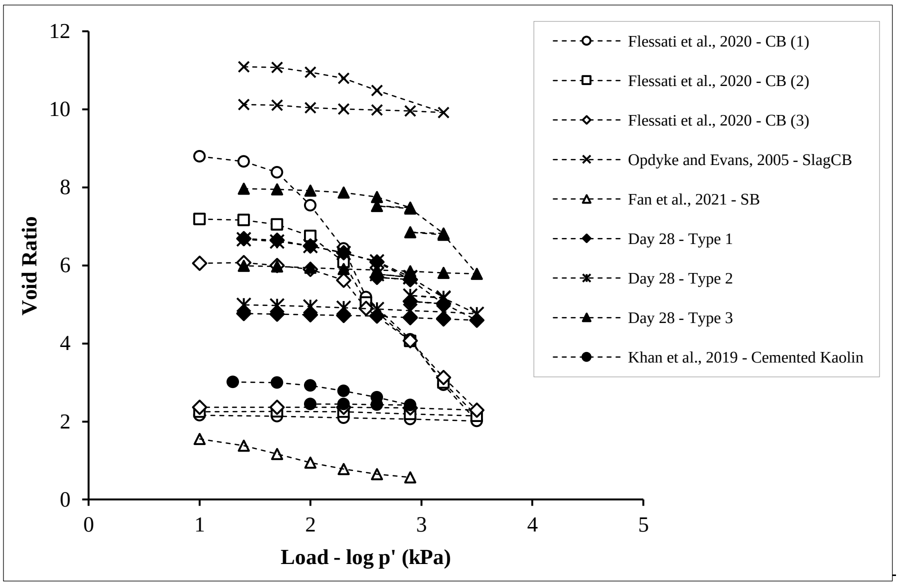


Figure 11. The comparison of the consolidation curve (void ratio – load) from the present study and relevant past studies

4.3.5. Preconsolidation Pressure

Preconsolidation pressure, in the geotechnical terms, is associated with the yield stress of the material, which [15] suggested that the yield stress of CB is attributed to the cementation bonding rather than its loading history. Given that the load applied to the samples is the highest to which they have ever been subjected, the CB samples may behave similarly to a soil that is normally consolidated. However, the presence of two log-linear portions (recompression and virgin compression) and an interpreted pre-consolidation pressure value suggest that the behavior of CB samples is similar to that of overconsolidated soil (Figures 11 and 12), and this behavior was consistent with the consolidation test performed on slag-CB sample by Opdyke & Evans [26]. For the 14-day curing period, samples with GGBS showed a more pronounced increase in pre-consolidation pressure (>500 kPa) than samples with more bentonite.

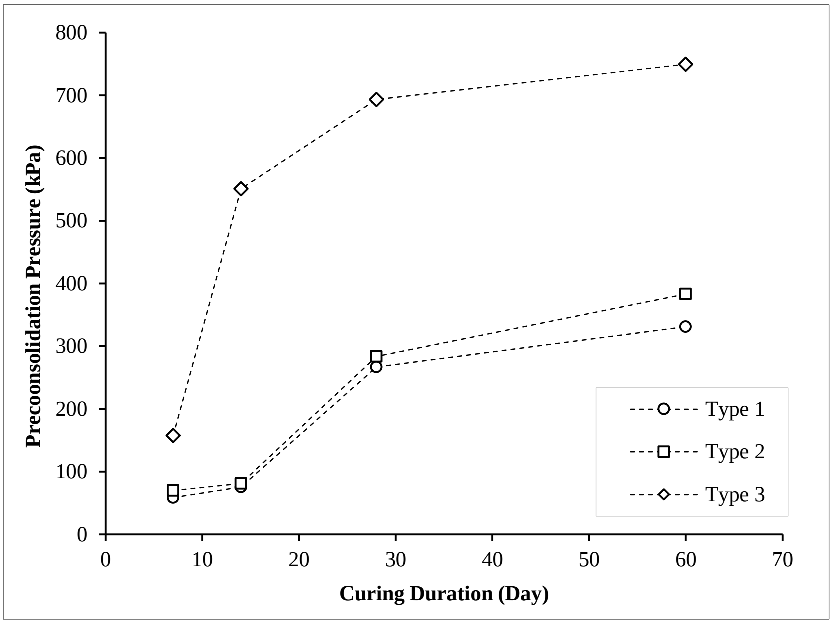


Figure 12. Pre-Consolidation Pressure

As mentioned in the literature review, the presence of sodium bentonite, a naturally occurring pozzolan, in CB samples greatly increases the reactivity to calcium hydroxide released during cement hydrolysis for the creation of pozzolanic cementation bonds. Such pozzolanic cementation bonds help refine the pore structure of materials, improve their microstructure and packing effectiveness, and continuously increase their strength [46, 47]. Additionally, the presence of mineral admixtures like PFA and GGBS contributes to the pozzolanic reaction, which converts calcium hydroxide into secondary calcium silicate hydrate gel, which is what gives cement-based materials their strength. This reaction results in the conversion of larger pores into finer pores and the production of denser calcium silicate hydrate gel [63]. These changes are similar to the behavior of overly consolidated soil, which has previously gone through a reduction in pore volumes due to the compression and dissipation of air and water in the voids, change in particle packing arrangement, deformation, and destruction of interparticle bonds. The pre-consolidation pressure marks the beginning of significant structural changes, such as the breakdown of interparticle bonds and interparticle displacement [64].

Therefore, it can be concluded that significant changes, such as the destruction of the interparticle bonds of hydrated bentonite and cementitious products, start to occur if the CB samples are loaded above the pre-consolidation pressure. As a result of the broken bonds, the particles become smaller and are packed more densely. Additionally, it is suggested that once shearing on the cementitious products starts, the frictional contacts between the solid particles inside the sample fabric (the sheared cementitious products and the hydrated bentonite particles) are what give CB its strength [65].

5. Conclusion

The attempt to compare the consolidation behaviour of CB to other geomaterials remains unsatisfactory due to significant differences in these materials' states of consolidation and fabric. The distinct characteristics of CB constituent materials (e.g., bentonite, cementitious materials) in comparison to other geomaterials make understanding CB consolidation behaviour more challenging. The current state of understanding CB consolidation behaviour necessitates further investigation, primarily due to how curing and changing the mix proportion affect its performance. The results of this study are intended to provide engineers with the necessary basis for engineering judgment in the design of CB barriers or other slurry walls, with a focus on how CB barriers respond to loading and their variation during the construction phase and their service life.

The study discovered that curing and changing the mix proportion contributed to the improvement of CB to consolidation (i.e., decreased compression), which can be attributed to the improvement of material fabric. Depending on the applied load and mix proportion, the consolidation characteristics of CB can be compared to those of overconsolidated clay. The presence of GGBS in the mixture contributed to a decrease in volumetric compressibility.

More bentonite was added to the CB samples, resulting in higher recompression indices. The presence of more bentonite increases the capacity of the CB to recover from the compression; however, further studies need to be undertaken to confirm this effect. Despite the low early strength gain caused by GGBS, the degree of consolidation decreased significantly once the CB samples were cured for more than 28 days. The pre-consolidation pressure increases with longer curing times and the addition of GGBS. In comparison to adding more bentonite, the addition of GGBS was found to be more effective in increasing pre-consolidation pressure.

6. Declarations

6.1. Data Availability Statement

The data presented in this study are available in the article.

6.2. Funding

The author received no financial support for the research, authorship, and/or publication of this article.

6.3. Acknowledgements

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6.4. Conflicts of Interest

The author declares no conflict of interest.

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