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# Hydraulic conductivity of filter cake modified by autoclaved aerated concrete powder and its mechanism

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**ABSTRACT**: Autoclaved aerated concrete powder (AACP), a kind of solid construction waste, is produced in huge quantities. However, the utilization of AACP is still limited due to its high porosity and low compressive strength. In this work, the chemical composition of AACP was obtained based on XRF analysis. Different amounts of AACP were used to modify the filter cake obtained from Shenzhen City for application in geotechnical projects. Permeability test and Atterberg limits test were carried out to investigate the engineering properties of the untreated and AACP-treated soil samples. The mechanism of improvement in engineering properties of AACP stabilized soil was also investigated. Test results showed that the hydraulic conductivity of the sample increased significantly after AACP treatment. The hydraulic conductivity of the compacted AACP/filter cake mixture containing 60% AACP (cured for 28 days) was 34.3 times higher than that of the compacted pure soil. The formation of aggregated soil particles and the increase in void ratio were the main causes of this phenomenon. AACP consists mainly of sand particles and has a strong water absorption ability. With the addition of AACP, the liquid limit and the plastic limit of the sample increased while the plasticity index decreased. The negative correlation between the hydraulic conductivity and the plasticity index suggested that the plasticity index could be used to estimate the hydraulic conductivity. The above results improve the reuse efficiency of AACP and propose a material for the modification of soft soils.

*Keywords: Hydraulic conductivity; Atterberg limits; Filter cake; Autoclaved aerated concrete powder (AACP)*

## 1 INTRODUCTION

Filter cakes with low strength and high compressibility have been produced in huge quantities in China in recent years (Wang et al., 2021). They are not suitable for use in road embankments, dams and typical geotechnical engineering projects. They are usually transported to landfills for disposal. However, this disposal method is currently being challenged by the increasing depletion of land resources. To address these problems and promote the use of filter cakes in engineering projects, some soil modification measures are required.

Cement and lime are commonly used to modify soil properties in the past decades (Wang et al., 2013; Jha & Sivapullaiah, 2015; Mahedi et al., 2020). However, they are expensive and energy-intensive. To overcome these problems, the use of suitable industrial wastes to modify soft soils has become a hot research topic. To date, the industrial wastes such as slag (Goodarzi & Salimi, 2015; Wanare et al., 2022), fly/bottom ash (Kim et al., 2005; Tastan et al., 2011), rubber (Soltani et al., 2018; Naseem et al., 2019), and autoclaved aerated concrete powder (AACP, Wang et al., 2022) have been concerned or investigated as additives by different scholars.

AACP is a kind of solid waste from the engineering construction field, which is produced in huge quantities all over the world. It has been widely accepted as a green material (Qu & Zhao, 2017). However, the treatment of it currently remains at the traditional simple backfilling and piling stage. AACP contains many micropores and tobermorite, resulting in its strong water absorption ability and excellent cation exchange capacity (Zhang et al., 2017). Thus, AACP may have great potential for use in soil modification. In general, the strength of the soil has usually been of much greater concern than that of the hydraulic conductivity. However, the long-term safety of a project is closely related to the hydraulic conductivity. This is mainly due to the fact that the consolidation rate of a material usually varies positively with its hydraulic conductivity. Wang et al. (2022) has demonstrated that the addition of AACP is helpful in improving the shear strength of the soil sample. However, the effect of AACP incorporation on soil hydraulic conductivity is not yet clear.

In this work, the Atterberg limits and permeability tests were performed on the samples with different AACP contents and curing times. That is, the effects of AACP content and curing time on the properties of the samples were investigated in this work. The changes in soil structure were also investigated by detailed scanning electron microscope (SEM) observations.

## 2 MATERIALS AND METHODS

### 2.1 Materials

Filter cake is a type of engineering waste soil consisting mainly of fine-grained soil particles. The filter cake used in this study is collected from Shenzhen City, China. Its specific gravity, natural water content, liquid limit, plastic limit and plasticity index are 2.67, 41.7%, 39.6%, 24.4% and 15.2, respectively. And the sand, silt and clay fractions are 23.65%, 57.37% and 18.98%, respectively. The filter cake is classified as lean clay (CL) according to the Unified Soil Classification System (ASTM D2487-17e1, 2020).

The AACP used in this study is collected from the Construction Solid Waste Processing Co., Ltd. in Shenzhen City, China. Table 1 shows the chemical compositions of AACP. It shows that the main oxides of AACP are $SiO_2$ and CaO. The particle size distributions of AACP and filter cake are shown in Figure 1. It should be noted that to eliminate the size effect on the test results, AACP finer than 5mm and 2mm were collected to prepare specimens for permeability and Atterberg limits tests, respectively.

***Table 1.*** *Chemical compositions of AACP*

| Oxide content (wt%) | $SiO_2$ | $Al_2O_3$ | CaO | $Fe_2O_3$ | MgO | $K_2O$ | $Na_2O$ | $SO_3$ |
|---|---|---|---|---|---|---|---|---|
| AACP | 37.0 | 6.53 | 28.0 | 2.43 | 1.23 | 1.76 | 0.82 | 1.03 |

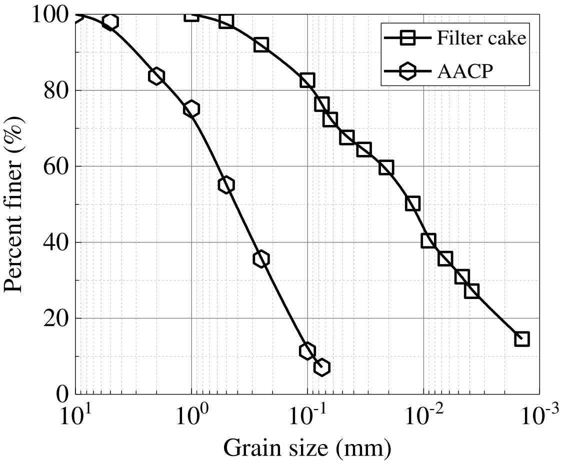


***Figure 1.*** *Particle size distributions of AACP and filter cake*

## 2.2 Test methods

To obtain uniform specimens, the selected AACP was manually mixed with the dried and sieved filter cakes prior to preparing the test specimens. These specimens were prepared at their optimum moisture content and maximum dry density. They were then placed in sealed polyethylene bags and cured at 20 ± 2 °C for 1, 7 and 28 days, respectively. The Atterberg limits test and permeability test were performed on the prepared specimens according to the Chinese standard GB/T 50123-2019 (2019). More specifically, the compacted specimens used for the Atterberg limits tests were carefully broken with a rubber hammer after curing for 1 and 28 days. This was mainly done to reduce experimental errors and to prevent damage to the aggregated soil particles. Following that, the specimens were mixed with a certain amount of water, e.g. 30%, 40% and so on. Once the homogeneous mixtures were obtained, Atterberg limits tests were carried out on them using a liquid and plastic limit united tester. The Atterberg limits of them were then obtained. The specimens used for the permeability tests were 61.8 mm in diameter and 40 mm in height. The hydraulic conductivity of each specimen was measured via the falling head method. In addition, all the specimens were pre-saturated in a vacuum saturator for 24 h using distilled water before permeability tests (Li et al., 2015). The details of the experimental program are tabulated in Table 2.

***Table 2.*** *Details of the experimental program*

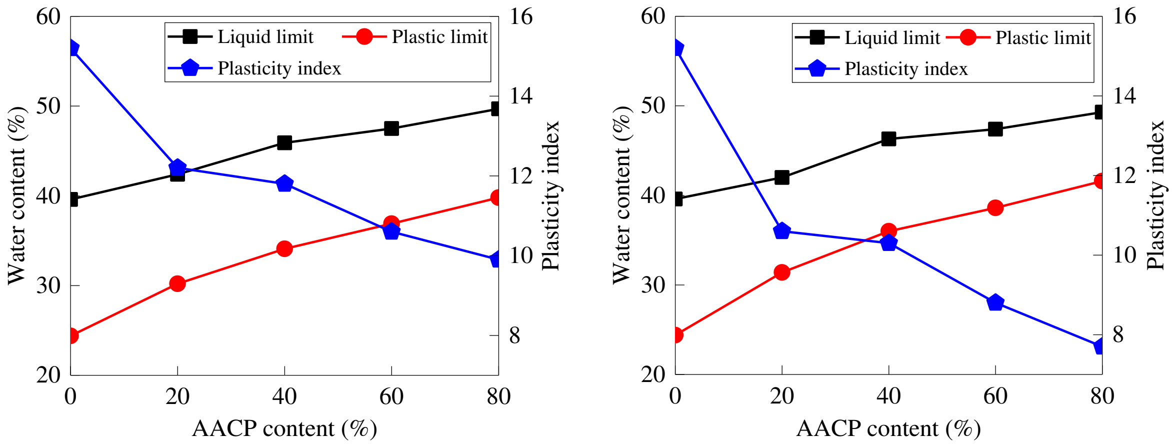
| Sample | Weight ratio of AACP to wet filter cake | Atterberg limits test | Permeability test |
|---|---|---|---|
| | | Curing periods (day) | |
| | | 1 / 28 | 1 / 7 / 28 |
| A1F5 | 20: 100 | + | + |
| A2F5 | 40: 100 | + | + |
| A3F5 | 60: 100 | + | + |
| A4F5 | 80: 100 | + | +[a] |

Note: (a) The hydraulic conductivity of the Sample A4F5 was measured after 1 d of curing.

## 3 RESULTS AND DISCUSSION

### 3.1 Atterberg limits

The Atterberg limits of different samples are shown in Figure 2. It was observed that with the increase in AACP content, both the liquid limit and the plastic limit increased while the plasticity index decreased. AACP is a porous material that contains many micropores (Ioannou et al., 2008; Thongtha et al., 2014; Qu & Zhao, 2017). The addition of AACP increased the number of micropores in the samples, thereby increasing the water holding ability of them (Locat et al., 1996). This explained the phenomenon that the liquid limit and the plastic limit increased with increasing AACP content. The addition of AACP also increased the sand fraction in the samples. Therefore, a decreasing trend in the plasticity index was observed. Additionally, it was also observed that with the increase in curing time, the plasticity index of the sample tended to decrease. Previous studies have shown that AACP has excellent cation exchange capacity and contains many soluble salts (Narayanan & Ramamurthy, 2000; Zhan et al., 2023). Therefore, for AACP/filter cake mixtures, the thickness of the DDL of clay particles may decrease with the prolonged curing time, while the number and/or volume of aggregated soil particles may gradually increase. The reduction in DDL of clay particles helps to reduce the liquid limit, while the rearrangement of soil particles helps to increase the liquid limit (Horpibulsuk et al., 2011; Jha & Sivapullaiah, 2015; Li et al., 2015). Under the combined action of these two factors, the liquid limit remained essentially constant, regardless of the curing time. The plastic limit is the water content as the soil approaches a certain shear resistance in the remolded position (Dash and Hussain, 2012; Jha & Sivapullaiah, 2015). The incorporation of AACP increased the electrolyte concentration and the viscosity of the pore fluid and changed the soil structure, increasing the interparticle shear resistance. Therefore, an increasing trend in the plastic limit was observed with increasing AACP amount and curing time.



(a) 1 d

(b) 28 d

***Figure 2.*** *Atterberg limits of different samples*

Figure 3 shows the plasticity index and liquid limit of the untreated and AACP-treated soil samples. All the stabilized soil samples were classified as low-plasticity silt (ML) based on the Unified Soil Classification System (ASTM D2487-17e1, 2020).

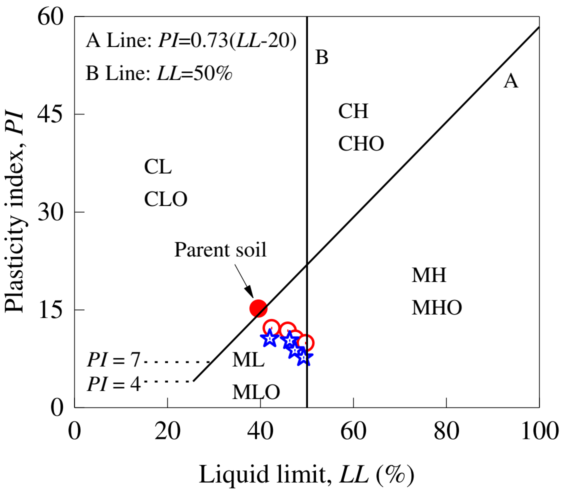


***Figure 3.*** *Plasticity chart*

To verify the hypothesis mentioned above, the SEM images obtained from several representative samples are presented in Figure 4. It was observed that the pure soil sample showed a compact fabric (Figure 4a). Upon the addition of AACP, some small aggregated soil particles were observed in the image (Figure 4b). With the increase in curing time, the size of the aggregated soil particles tended to become larger (Figure 4c). That is, the addition of AACP caused the soil structure to change from a relatively dispersed to a flocculated arrangement. This agreed well with the above test results. Moreover, similar observations were also found by Sivapullaiah et al. (2000) and Dash & Hussain (2012) when lime was used as an additive to modify soft soils, indicating that there are some similarities in the soil stabilization mechanism between AACP-based stabilization and lime-based stabilization.

(1) Pure soil (2) A3F5-1 d (3) A3F5-28 d

***Figure 4.*** *SEM images of different samples*

### 3.2 Hydraulic conductivity

Table 3 shows the hydraulic conductivity of the compacted specimens with 0%, 20%, 40%, 60% and 80% AACP content. It was observed that the measured values of hydraulic conductivity varied from $2.10\times10^{-8}$ cm/s to $7.21\times10^{-7}$ cm/s. And the hydraulic conductivity of the sample tended to increase with increasing AACP content and curing time.

***Table 3.*** *Hydraulic conductivity of the compacted AACP/filter cake mixtures*

| Sample | Initial void ratio | Hydraulic conductivity/ (cm/s) | | |
|---|---|---|---|---|
| | | 1 d | 7 d | 28 d |
| A1F5 | *e* = 0.67 | $5.36\times10^{-8}$ | $1.29\times10^{-7}$ | $1.38\times10^{-7}$ |
| A2F5 | *e* = 0.70 | $1.04\times10^{-7}$ | $4.81\times10^{-7}$ | $5.36\times10^{-7}$ |
| A3F5 | *e* = 0.77 | $2.26\times10^{-7}$ | $6.22\times10^{-7}$ | $7.21\times10^{-7}$ |
| A4F5 | *e* = 0.87 | $6.70\times10^{-7}$ | - | - |

Note: The initial void ratio and hydraulic conductivity of the compacted pure soil sample are 0.66 and $2.10\times10^{-8}$ cm/s, respectively.

Wang et al. (2022) indicated that the maximum dry density of the sample tended to decrease with the increase in AACP content. Although all the samples were prepared at their maximum dry density, the void ratio of them showed an increasing trend with the addition of AACP (Table 3). In addition, with the prolonged curing time, a more open fabric was observed in the mixtures due to the formation of aggregated soil particles (Figure 4). Therefore, the changes in void ratio and the rearrangement of soil particles were mainly responsible for this phenomenon.

### 3.3 Relationship between plasticity index and hydraulic conductivity

Figure 5 shows the relationship between plasticity index and hydraulic conductivity. As shown in Figure 5, the hydraulic conductivity of the sample tended to decrease as the plasticity index increased.

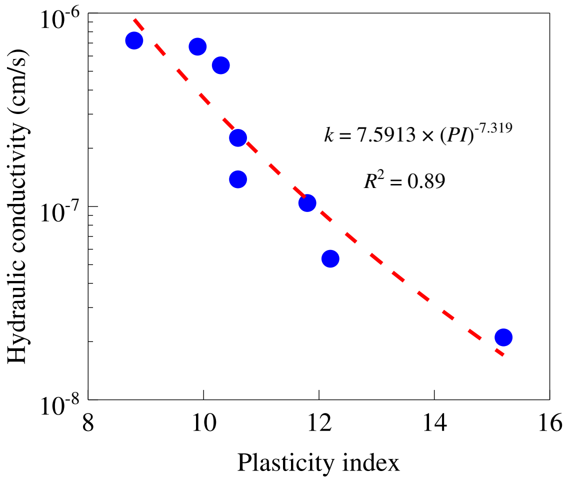


***Figure 5.*** *Relationship between plasticity index and hydraulic conductivity*

Equation (1) gives the best fitting equation for hydraulic conductivity (*k*) as a function of plasticity index (*PI*). The coefficient of determination ($R^2$) was 0.89, indicating that the prediction accuracy was good. Therefore, the hydraulic conductivity of a sample can be estimated from its plasticity index.

$$k = 7.5913 \times (PI)^{-7.319};\ R^2 = 0.89 \qquad (1)$$

## 4 CONCLUSIONS

This work investigates the effects of AACP content and curing time on the hydraulic conductivity and Atterberg limits of the samples. The following conclusions can be drawn from this work.

1. With the addition of AACP, the liquid limit and plastic limit of the sample tended to increase, while the plasticity index tended to decrease. AACP altered the engineering properties of the filter cake by changing the particle size distributions and soil structures.

2. The hydraulic conductivity of the compacted samples increased with the increase in AACP content and curing time. When AACP content increased from 0% to 60%, the hydraulic conductivity of the sample (cured for 28 d) increased from $2.10\times10^{-8}$ cm/s to $7.21\times10^{-7}$ cm/s. The presence of the higher void ratio and the more open fabric were mainly responsible for this phenomenon. Moreover, the plasticity index could be used to predict the hydraulic conductivity of the compacted samples and the prediction accuracy was good.

3. Based on the hydraulic conductivity of the untreated and AACP-treated soil samples, consolidation of the AACP-treated soil samples would be completed in less time under the same conditions. The AACP/filter cake mixtures are suitable for use in conventional geotechnical projects.

## 5 ACKNOWLEDGEMENTS

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