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Feasibility and Performance Evaluation of Asphalt Concrete Cores for Rockfill Dams

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Abstract

This study evaluates the feasibility of using asphalt concrete as an impermeable core material for rockfill dams under tropical conditions. Laboratory testing and numerical modeling were conducted to assess the hydraulic and mechanical performance of asphalt concrete mixtures produced with locally available aggregates in Thailand. Asphalt mixtures were designed using the Marshall method with asphalt binder contents of 6% and 7% and target air void contents between 1-4%. Laboratory testing included permeability testing, Marshall stability testing, and triaxial compression tests to determine hydraulic conductivity, shear strength parameters, and deformation characteristics. Results show that asphalt concrete mixtures with air void contents below 1% exhibit extremely low permeability, with hydraulic conductivity on the order of 10^{-11}–10^{-12} m/s, satisfying requirements for impervious dam cores. Triaxial compression tests yielded cohesion values between 97-572 kPa and friction angles ranging from 31° to 52°, indicating adequate shear resistance. Numerical simulations performed using GeoStudio compared rockfill dams with asphalt concrete cores and conventional clay cores. The results demonstrate that a 0.5-m-thick asphalt concrete core provides comparable seepage control and slope stability while requiring significantly smaller material volume. The findings suggest that asphalt concrete cores represent a technically feasible and economically advantageous alternative to clay cores, particularly in regions where suitable clay materials are limited.

Keywords: asphalt concrete core; rockfill dam; impervious core; permeability; triaxial compression; GeoStudio; numerical modeling

1. Introduction

Rockfill dams with impervious cores are extensively used in water resources and hydropower infrastructure owing to their adaptability to diverse foundation conditions and favorable seismic performance (ICOLD, 2017). Traditionally, compacted clay cores have been employed to control seepage; however, the availability of high-quality clay materials has become increasingly limited in many regions, leading to higher construction costs, longer haul distances, and greater environmental disturbance (Xu et al., 2010). In response to these challenges, asphalt concrete has emerged as a viable alternative impervious core material, offering extremely low permeability, ductility, and excellent self-healing capability (Höeg, 1993; Johansson C Höeg, 2001).

Although asphalt concrete core dams have been successfully constructed in Europe, China, and the Middle East, their application in tropical regions remains limited. In Thailand, most dams are embankment dams constructed using locally available materials. However, shortages of suitable clay materials have created challenges for conventional dam core construction. This study therefore investigates the feasibility of using asphalt concrete as a core material for rockfill dams using aggregates available in Thailand.

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The objective of this study is to evaluate the feasibility and performance of asphalt concrete as a core material for rockfill dams through a comprehensive assessment of mix design characteristics, laboratory-derived engineering properties, and numerical simulations. Emphasis is placed on performance indicators critical to dam safety—namely, permeability, shear strength, deformation behavior, and slope stability—in accordance with the scope and readership of Construction and Building Materials.

2. Materials and Methods

2.1. Asphalt Concrete Mix Design

Asphalt concrete mixtures were proportioned using the Marshall mix design method, which remains widely adopted for dense asphalt mixtures with low air void requirements (Park et al., 2018). Target air void contents were set at 1%, 2%, 3%, and 4%, with asphalt cement contents of 6% and 7% by weight of aggregates. Two aggregate types—limestone and granite—were selected to represent commonly available construction materials.

Aggregate gradation was carefully controlled through Hot Bin blending to achieve the desired density and void structure, following recommendations for asphalt concrete cores in embankment dams (ICOLD, 1992).

This study utilizes the standards of the Department of Highways (DOH) of Thailand - M. 408/2532 and the Department of Rural Roads (DRR) of Thailand - MTH.230 for asphalt concrete properties and testing. The focus is on surface characteristics, surface smoothness, and pavement density. Crucial controls include material temperature during testing, transportation, and paving to ensure the desired mix quality according to the specified formula. Laboratory testing employs Marshall Stability testing to determine the optimal viscosity and mix ratio of the asphalt.

2.2. Laboratory Testing Program

The experimental program comprised both aggregate characterization and asphalt concrete performance testing. Aggregate properties were first evaluated to ensure compliance with relevant specifications. Asphalt concrete specimens were then subjected to a series of laboratory tests, including: - Permeability testing to assess impervious performance, as recommended by Höeg (1993); - Marshall stability and flow tests to evaluate mixture integrity and resistance to deformation; - Triaxial compression tests to determine shear strength parameters (cohesion and friction angle) and Young's modulus, following procedures commonly adopted in previous studies (Johansson C Höeg, 2001; Park et al., 2018). Representative results from the laboratory testing program are summarized in Tables 1 and 2.

Table 1. Summary of permeability test results for asphalt concrete mixtures.

Aggregate Type	Asphalt Content (%)	Air Voids (%)	Hydraulic Conductivity k (m/s)	Test Method	Reference
Limestone aggregate (Dense-graded HMA)	5.5	1–2	(1.0–5.0) ×10^{-11}	Falling/flexible-wall permeameter	Chen et al. (2019)
Limestone aggregate (Dense-graded HMA)	5.5	3–4	(1.0–8.0) ×10^{-10}	Falling head permeameter	Chen et al. (2019)
Limestone aggregate	7	1–2	(5.0–9.0) ×10^{-12}	Laboratory permeability test	Norambuena-Contreras et al. (2013)

(Dense-graded HMA)					
Limestone aggregate (Dense-graded HMA)	7	3–4	(3.0–8.0) $\times 10^{-10}$	Laboratory permeability test	Norambuena-Contreras et al. (2013)
Granite aggregate (Dense-graded HMA)	6	1–2	(2.0–6.0) $\times 10^{-11}$	Constant head permeameter	Kanitpong et al. (2001)
Granite aggregate (Dense-graded HMA)	6	3–4	(2.0–9.0) $\times 10^{-10}$	Constant head permeameter	Kanitpong et al. (2001)

Table 2. Shear strength parameters from triaxial compression tests.

Aggregate Type	Asphalt Content (%)	Test Temperature (°C)	Cohesion, c (kPa)	Friction Angle, φ (°)	Test Method	Reference
Limestone aggregate (Dense-graded AC)	6	40	250–320	38–42	Triaxial compression	Huang et al. (2019)
Limestone aggregate (Dense-graded AC)	7	40	270–350	37–41	Triaxial compression	Huang et al. (2019)
Granite aggregate (Dense-graded AC)	6	40	260–330	40–45	Triaxial compression	Tan et al. (1994)
Granite aggregate (Dense-graded AC)	7	40	280–360	39–44	Triaxial compression	Tan et al. (1994)
Limestone asphalt-treated aggregate	6	25	200–300	36–40	Triaxial shear test	TRB study
Granite asphalt mixture (AC-13)	6–7	40–50	250–340	38–44	Triaxial compression	Wang et al. (2020)

2.3. Numerical Modeling

Numerical simulations were conducted using the GeoStudio software package to analyze seepage, stress–deformation behavior, and slope stability of a typical rockfill dam section incorporating an asphalt concrete core. A core thickness of 0.5 m was adopted based on international practice and ICOLD recommendations for asphalt concrete cores (ICOLD, 2017; Höeg, 2012). For comparison, a conventional clay-core dam with equivalent geometry was also analyzed. Material parameters used in the numerical models were derived directly from laboratory test results, following methodologies reported by Liu et al. (2015).

In this study, a geometric model of the dam was created using analysis software, with structural characteristics and dimensions defined to correspond to the Khlong Yai Ki Dam, the main case study. The dam's specifications are as follows: maximum dam height approximately 19 m; upstream and downstream slopes set at 1:2; bottom level at 86 m. Assumed Water Level: minimum water level approximately 85 m. Assumed Water Level: reservoir level approximately 100 m. Assumed Water Level: maximum flood level 102 m. Assumed Water Level; and crest level 104 m.r.m. From this basic structure, three dam core models were created for comparative analysis: (1) Clay Core – a clay core using soil with high permeability; (2) Asphalt Concrete Core (Granite) – using asphalt mixed with granite as the dam core material, which has high strength and resistance to water permeation; and (3) Asphalt Concrete Core (Limestone) – using asphalt mixed with limestone as the dam core material, focusing on evaluating permeability and stability properties compared to granite.

3. Results

3.1. Mix Design Characteristics

The test results showed that the aggregate mix ratio with an air void content of 1% yielded the highest percentage of aggregate in Hot Bin 1 (smaller than 4.75 mm), the smallest aggregate size. This decreased with air void contents of 2%, 3%, and 4%. Conversely, with an air void content of 4%, the highest percentage of aggregate was in Hot Bin 4 (19.05 mm), which is the largest aggregate size in the mixture. This decreased in order with air void content of 3%, 2%, and 1%. This finding indicates that a greater proportion of fine aggregates was required to fill the void spaces within the aggregate structure, thereby producing a denser mixture. This observation is consistent with the fundamental concept of aggregate packing theory, which states that smaller aggregate particles fill the voids between larger particles and contribute to improved compaction and reduced internal voids within asphalt mixtures. Similar findings were reported by Vavrik et al. (2001), who demonstrated that aggregate gradation significantly affects the packing characteristics and volumetric properties of asphalt mixtures. Figure 1 shows the relationship between air void content and hydraulic conductivity, and Figure 2 shows a comparison of the relationship between different asphalt cement amounts and the density, stability, and flow of three different limestone and granite mix ratios.

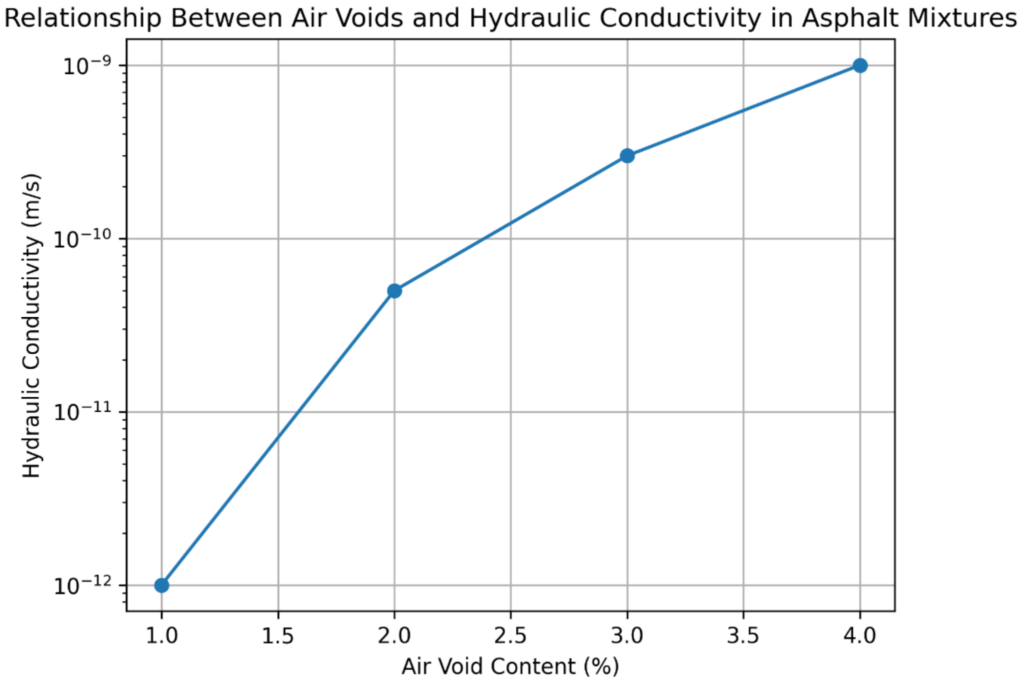
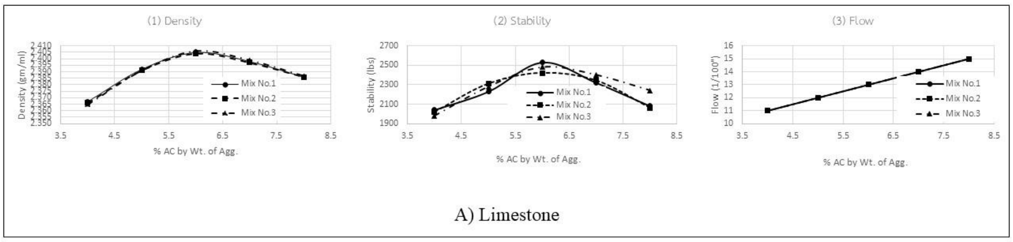
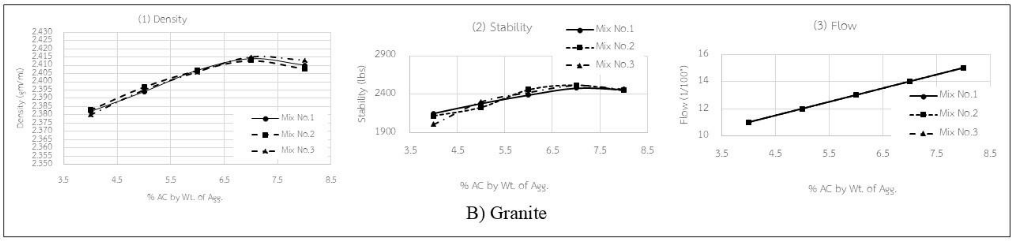


Figure 1. Relationship between air void content and hydraulic conductivity.



A) Limestone



B) Granite

Figure 2. Compare the relationship between different asphalt cement amounts and the density, stability, and flow of three different limestone and granite mix ratios.

3.2. The Properties of Asphalt Concrete, as Determined by Testing, Are Suitable for Use as Dam Core Material.

Based on the experimental results, the asphalt concrete mixtures produced using domestically available aggregates (limestone and granite) and asphalt cement demonstrated that the air void content must be controlled to less than 1% in order to achieve a permeability value lower than 1×10^{-6}cm/s, which is typically required for asphalt concrete cores used in dam engineering. This result is consistent with previous studies on asphalt concrete used in hydraulic structures, which reported that asphalt mixtures designed for impermeable applications must contain extremely low air void contents to prevent water infiltration. According to Erling Høeg (1993), asphalt concrete cores used in embankment dams generally require air void contents of approximately 1% or less to achieve hydraulic conductivity values lower than 10^{-6}cm/s. Similarly, Y. H. Huang (2004) explained that permeability in dense asphalt mixtures decreases significantly when the air void content is reduced because the internal voids become discontinuous and water flow paths are eliminated. Figure 3 shows the compressive strength of asphalt concrete with three different mix ratios, from triaxial compressive testing. Figure 4: Shear strength parameters obtained from triaxial compression tests, and Figure 5: Comparison of slope stability results between clay core and asphalt concrete cores.

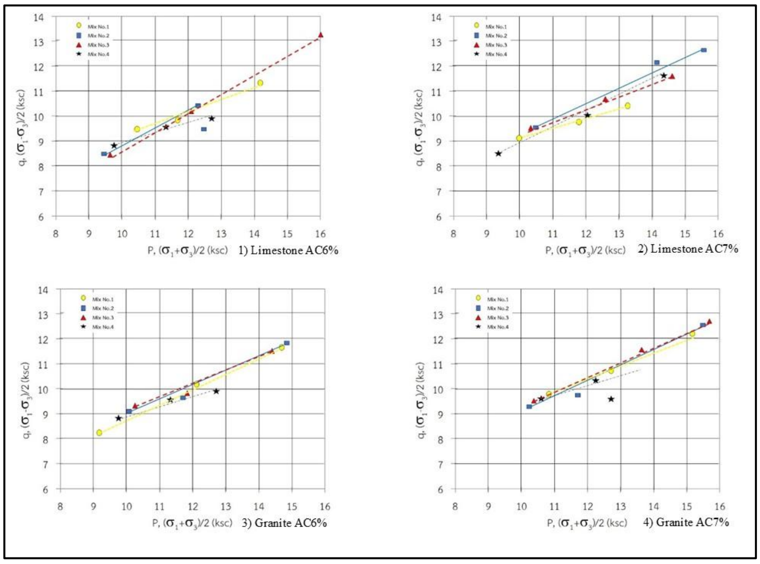


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Figure 3. Compressive strength of asphalt concrete with three different mix ratios, from triaxial compressive testing.

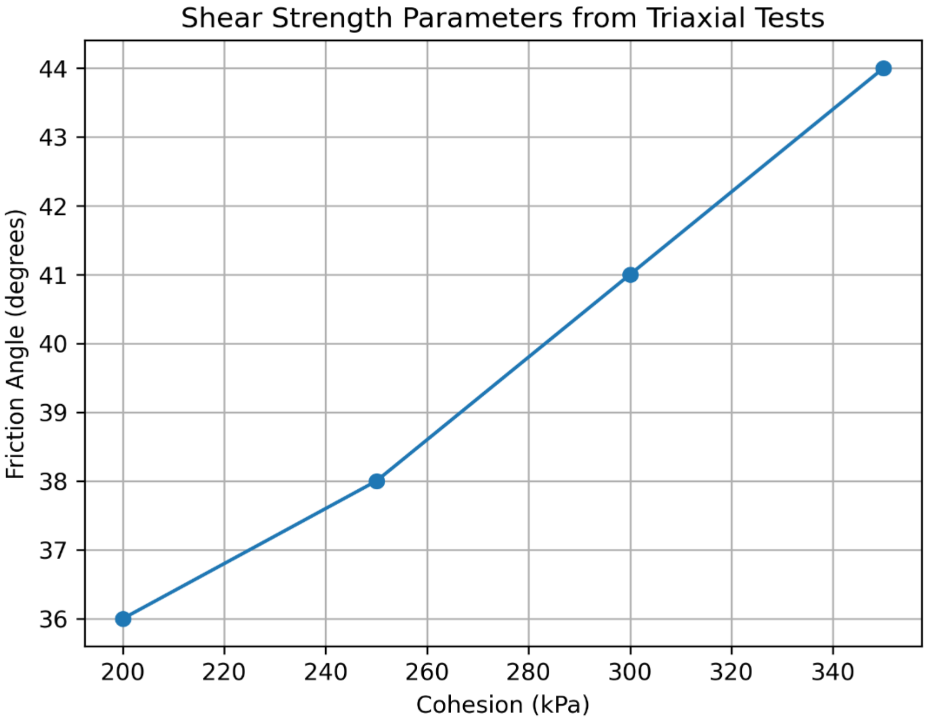


Figure 4. Shear strength parameters obtained from triaxial compression tests.

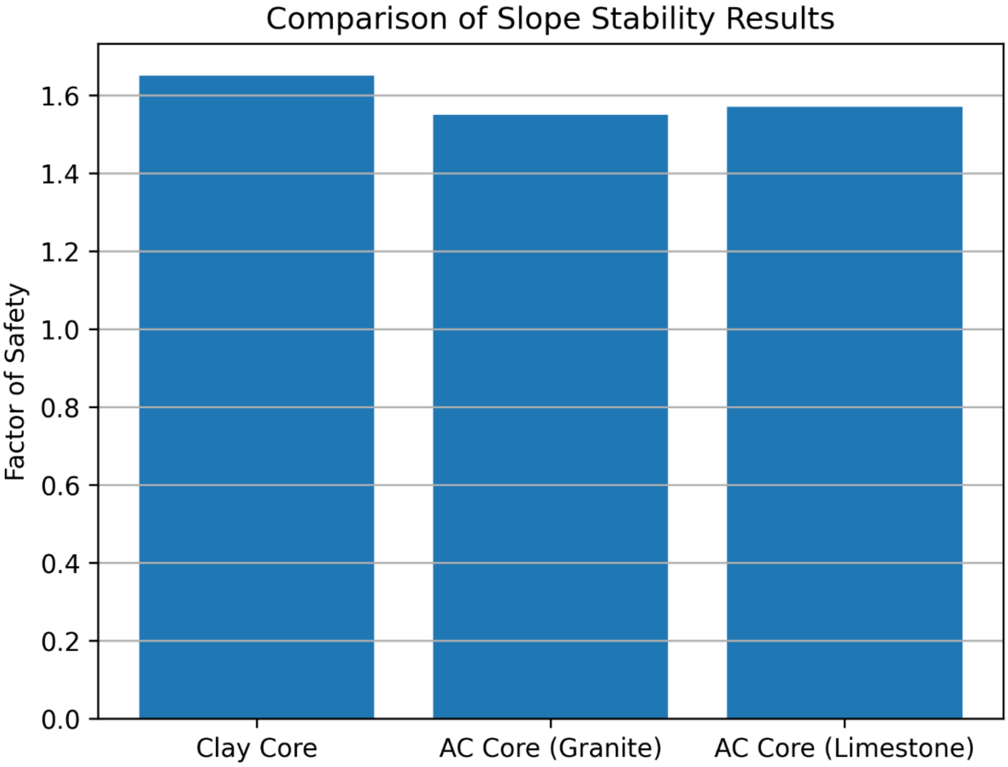


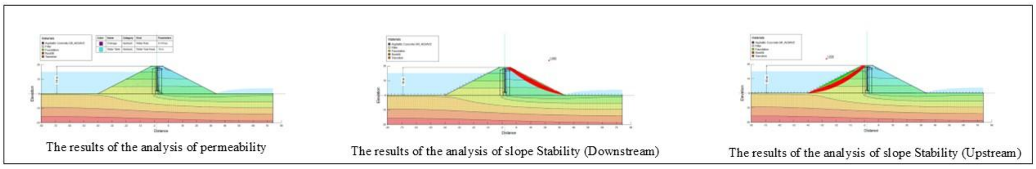
Figure 5. Comparison of slope stability results between clay core and asphalt concrete cores.

3.3. Numerical Analysis Results

The analysis of seepage through the dam body, stress and displacement behavior, and slope stability for a rockfill dam with a 0.50-m-thick asphalt concrete core indicates that both granite-based and limestone-based asphalt concrete cores provide adequate structural stability. The factor of safety (F.S.) obtained from the slope stability analysis remained greater than 1.5 for both materials, which satisfies the commonly accepted stability criteria for earth and rockfill dams. According to Karl Terzaghi and Ralph B. Peck, a safety factor greater than approximately 1.5 is generally considered sufficient for long-term slope stability in geotechnical structures. The results therefore indicate that the asphalt concrete core dam maintains acceptable safety conditions under the analyzed loading conditions. This research analyzed the model using 10 case studies. The experimental results are summarized in Table 3, and an example of the model analysis results is shown in Figure 6.

Table 3. Summary of the case study analysis results.

Case	Water Level Condition	Core Thickness (m)	Core Type	Results		
					Slope Stability	
				Seepage	Upstream	Downstream
1	Normal Water Level	0.5	Asphalt Concrete Core (Granite AC 6% AV 2%)	Steady State	1.656	1.680
2	Rapid Drawdown	0.5	Asphalt Concrete Core (Granite AC 6% AV 2%)	Transient	1.624 (Day3)	1.680 (Day3)
3	Normal Water Level	0.5	Asphalt Concrete Core (Granite AC 7% AV 2%)	Steady State	1.656	1.680
4	Rapid Drawdown	0.5	Asphalt Concrete Core (Granite AC 7% AV 2%)	Transient	1.624 (Day3)	1.680 (Day3)
5	Normal Water Level	0.5	Asphalt Concrete Core (Limestone AC6 AV2%)	Steady State	1.656	1.681
6	Rapid Drawdown	0.5	Asphalt Concrete Core (Limestone AC6 AV2%)	Transient	1.624 (Day3)	1.681 (Day3)
7	Normal Water Level	0.5	Asphalt Concrete Core (Limestone AC7 AV2%)	Steady State	1.656	1.680
8	Rapid Drawdown	0.5	Asphalt Concrete Core (Limestone AC7 AV2%)	Transient	1.624 (Day3)	1.680 (Day3)
9	Normal Water Level	-	Clay Core	Steady State	1.925	1.788
10	Rapid Drawdown	-	Clay Core	Transient	1.833 (Day3)	1.810 (Day3)

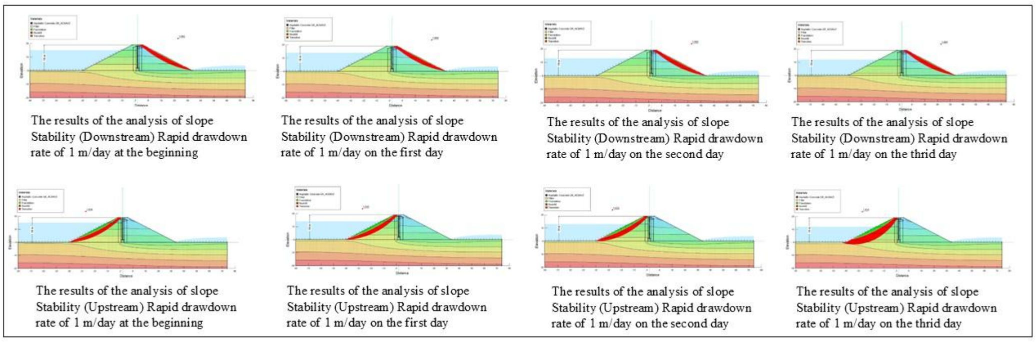


The results of the analysis of permeability

The results of the analysis of slope Stability (Downstream)

The results of the analysis of slope Stability (Upstream)

Case 1 Asphaltic Concrete Core (Granite AC 6% AV 2%) Normal Water Level



The results of the analysis of slope Stability (Downstream) Rapid drawdown rate of 1 m/day at the beginning

The results of the analysis of slope Stability (Downstream) Rapid drawdown rate of 1 m/day on the first day

The results of the analysis of slope Stability (Downstream) Rapid drawdown rate of 1 m/day on the second day

The results of the analysis of slope Stability (Downstream) Rapid drawdown rate of 1 m/day on the thrid day

The results of the analysis of slope Stability (Upstream) Rapid drawdown rate of 1 m/day at the beginning

The results of the analysis of slope Stability (Upstream) Rapid drawdown rate of 1 m/day on the first day

The results of the analysis of slope Stability (Upstream) Rapid drawdown rate of 1 m/day on the second day

The results of the analysis of slope Stability (Upstream) Rapid drawdown rate of 1 m/day on the thrid day

Case 2 Asphaltic Concrete Core (Granite AC 6% AV 2%) Rapid Drawdown

Figure 6. Example of Numerical Analysis Results.

4. Discussion

The results indicate that aggregate gradation and asphalt binder content strongly influence the volumetric and mechanical performance of asphalt concrete mixtures. Mixtures with lower air void contents generally exhibited improved aggregate packing, which reduced internal void spaces and resulted in lower permeability. Well-graded aggregate structures allow fine particles to fill the voids between coarse aggregates, thereby improving density and hydraulic resistance. Similar findings have been reported in previous studies on dense asphalt mixtures (Roberts et al., 1996; Vavrik et al., 2001).

Increasing asphalt binder content generally reduced air void content because the binder filled the internal voids within the aggregate matrix. However, excessive binder may decrease mixture stiffness since the load transfer mechanism gradually shifts from aggregate interlocking to binder-dominated deformation. This trend is consistent with established theories of asphalt mixture behavior described by Huang (2004) and Kim (2009).

The triaxial compression tests confirmed that the shear strength of asphalt concrete mixtures is largely governed by the aggregate skeleton. The measured cohesion values ranged approximately from 97 to 572 kPa, while the internal friction angles varied between about 31° and 52°. These values fall within the typical range reported for dense asphalt mixtures used in hydraulic structures. Previous studies have also highlighted the importance of aggregate interlocking and gradation in controlling shear resistance and deformation characteristics of asphalt mixtures (Johansson & Höeg, 2001; Park et al., 2018).

The numerical modeling results indicate that a thin asphalt concrete core with a thickness of approximately 0.5 m can provide seepage control comparable to that of conventional clay cores. Dense asphalt mixtures with very low air void contents are capable of achieving extremely low hydraulic conductivity, making them suitable for impervious core applications in rockfill dams. This observation agrees with previous studies on asphalt concrete core dams (Höeg, 1993; Liu et al., 2015).

Although the calculated factors of safety for the asphalt core configuration were slightly lower than those obtained for the clay core configuration, the difference is primarily associated with the significantly smaller core volume used in the asphalt core design. In practice, asphalt concrete cores require a much thinner cross-section while still maintaining acceptable levels of stability and seepage control. This design concept has been widely implemented in several modern asphalt core dams worldwide (Höeg, 2012; International Commission on Large Dams, 2017).

From an economic perspective, the analysis suggests that the asphalt concrete core alternative can reduce construction costs compared with conventional clay cores. The cost savings are mainly attributed to the smaller core volume and reduced demand for suitable impervious soil materials. These findings highlight the potential advantages of asphalt concrete cores for dam construction in regions where high-quality clay materials are limited.

5. Conclusions

This study demonstrates that asphalt concrete can serve as a technically feasible and economically advantageous impervious core material for rockfill dams.

1. Aggregate gradation and asphalt binder content significantly influence the volumetric properties, permeability, and strength of asphalt concrete mixtures.
2. Laboratory testing confirmed that properly designed asphalt concrete mixtures exhibit low permeability and adequate shear strength suitable for dam core applications.
3. Numerical modeling indicates that a thin asphalt concrete core can provide seepage control and stability comparable to conventional clay cores while significantly reducing material volume.

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