Utilizing Crushed Volcanic Scoria as a Subsurface Medium for Water Storage in Arid Regions: A Comparative Laboratory Study

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ABSTRACT

Water storage systems face major challenges in arid regions, such as the Kingdom of Saudi Arabia (KSA), where high evaporation and seepage significantly reduce the efficiency of traditional open reservoirs. In addition, the construction of large steel and concrete tanks is costly, limiting their use outside urban areas. This study experimentally evaluates Crushed Volcanic Scoria (CVS) as a sustainable medium for subsurface water storage, and compares its performance with Crushed Granite (CG) and natural sand. Laboratory experiments were conducted using transparent acrylic cylinders to measure the Water Storage Capacity percentage (WSC%) and dry density across three particle size groups (16–12.5 mm, 12.5–9.5 mm, and 9.5–4.75 mm). For sand, three grain size types were tested for comparison. All materials were oven-dried, placed in cylinders, and saturated to determine their void-filling capacity. The results showed that CVS achieved the highest WSC% (72.7–62.8%), approximately 22% higher than CG and 30% higher than sand. The dry density of CVS (404.3–500.8 kg/m^3) was markedly lower than that of CG (1532.8–1554.0 kg/m^3) and sand (1468.7–1528.7 kg/m^3), confirming its light and porous nature. These properties are attributed to the vesicular structure and irregular particle geometry of CVS, which result in higher porosity and water retention. Overall, it is demonstrated that CVS is a technically effective, economical, and locally available alternative for subsurface water storage in arid environments, reducing reliance on costly conventional storage systems.

Keywords-crushed volcanic scoria; water storage capacity; subsurface water storage; crushed granite; arid regions; Saudi Arabia

I. INTRODUCTION

The KSA faces ongoing challenges in securing potable water resources. The rapid population growth and expansion of agricultural and industrial activities are driving the rising demand for water. Excluding the mountains of the southwest and a limited area of the central regions of the country, most of KSA receives less than 100 mm of rainfall annually [1, 2]. This scarcity has left the KSA heavily dependent on two main sources: desalinated seawater and groundwater [3]. Desalination provides approximately two-thirds of the municipal water supply, whereas groundwater meets most agricultural demands [4, 5]. However, both sources have limitations. Desalination is highly energy-intensive and depends mainly on fossil fuels [6]. This reliance results in high costs and contributes significantly to environmental degradation through concentrated brine discharge and carbon emissions [7]. In [8], it was shown that fossil-fuel powered desalination produces significant emissions, generating 6.7 kg CO_2-eq/m^3. Furthermore, authors in [9] conducted a comprehensive review documenting that hypersaline brine discharge containing chemical additives can spread across the seabed up to 5 km from the discharge point, affecting benthic organisms. At the same time, reliance on groundwater steadily depletes finite reserves. This dependence creates sustained pressure on financial resources, reduces natural reserves, and increases the environmental challenges that KSA is facing.

Water storage facilities play an essential role in ensuring reliable water management. Several methods are currently applied in KSA to store water, including open surface dams and steel or concrete tanks. Open surface dams are built mainly for rainwater harvesting. Until 2022, KSA operated 522 dams with a total storage capacity of approximately 2.3 billion m³. However, the water stored in dams is subject to significant evaporation losses. Elevated temperatures in KSA and the large surface areas of the dams accelerate the evaporation of extensive volumes of water [10]. Many of these dams are constructed across wadi channels to capture stormwater, but a large percentage of the stored water is lost due to evaporation, reducing their long-term effectiveness [11, 12]. In [13], it was reported that the high evaporation rates in KSA result from the combined effects of high temperatures, which increase the kinetic energy of water molecules, and the extensive surface area of large dam reservoirs exposed to hot, dry, and windy conditions. In addition, the low humidity, intense solar radiation, and frequent wind activity in the region further intensify water loss through evaporation [14, 15]. Such losses pose significant challenges for water management, particularly in the KSA, which is already facing water scarcity and high demand.

Steel and concrete tanks offer better water storage and effectively prevent evaporation losses compared to open-surface reservoirs. These structures are widely used in urban and industrial areas, where long-term storage and distribution control are critical [16]. However, their construction entails high financial investment, involving expensive materials, specialized labor, and complex engineering requirements. In addition, they demand regular inspection, cleaning, and maintenance to prevent corrosion, cracking, and contamination, which further increases their operational costs. Such expenses are particularly difficult to justify when the stored water is intended for low revenue uses, such as agricultural irrigation or livestock watering, where cost efficiency is a key priority. Consequently, their adoption in remote and the rural regions of KSA remains limited. As water demand continues to rise across KSA, the need for affordable, low-maintenance, and environmentally sustainable storage alternatives has become one of the nation's most urgent challenges.

Sand dams are used in some arid regions to harvest rainwater during the wet seasons and make it available during dry periods. In this system, water settles into the voids between sand particles, forming an artificial underground reservoir. This process reduces evaporation losses by storing water below the surface and requires minimal maintenance [17]. Storing water below ground significantly reduces evaporation losses compared to open reservoirs, as the water is shielded from direct sunlight and heat [18]. Authors in [19] demonstrated through field studies in Tanzania that sand dams can protect water from evaporation while naturally filtering water through infiltration into sand, helping to raise groundwater levels in surrounding areas. In [20], it was demonstrated that the evaporation losses of water stored 60–90 cm into the sand are much less than when the water is stored in open reservoirs. Beyond their technical role, sand dams support rural livelihoods by improving water security, reducing vulnerability to drought, and strengthening community resilience to climate change [20].

Despite these advantages, sand dams face limitations. Because sand has a relatively low void capacity, the ratio of stored water to dam volume remains limited [19, 21]. Sand dams store only between 20% and 35% of their volume as usable water, meaning that most of the dam's physical volume is not available for water extraction [18]. Owing to these physical constraints, sand dams are ideal as decentralized, community-based solutions but are insufficient for cities or industries that require much higher volumes [22]. Consequently, while effective at the village and small-farming levels, sand dams cannot fully meet larger-scale water demands.

CVS may offer a promising alternative to sand for constructing subsurface water storage systems in arid regions such as KSA. Significant deposits of volcanic scoria are found in the western regions of the KSA, particularly in the Harrat Rahat and Harrat Khaybar volcanic fields. Harrat Rahat alone covers roughly 2,000 km^2 and contains basaltic lava that reaches up to 300 m in thickness [23]. It is one of the largest Cenozoic volcanic fields in the region, featuring more than 900 volcanic vents including scoria cones [24, 25]. Similarly, Harrat Khaybar is characterized by extensive basaltic lava sheets [26]. The Harrat Khaybar, the larger in the area (12,000-14,000 km^2), features extensive basaltic lava fields formed by eruptions over approximately 5 million years, with the last eruption recorded between 600 and 700 AD [27]. It is characterized by various volcanic landforms, including basaltic lava flows, lava domes, and scoria cones.

CVS is produced by crushing volcanic stone and is used for various construction purposes in KSA. CVS possesses a porous structure formed by vesicles, which are gas bubbles trapped during the rapid cooling and degassing of lava [28, 29]. As lava cools quickly, gases exsolve from the melt and create vesicles that become trapped within the solidifying rock, producing significant porosity [30, 31]. This porosity allows it to retain more water than denser materials such as sand and gravel. In addition, CVS is lightweight due to its porous, vesicular structure, which eases handling and transport. These properties make it a cost-effective and sustainable material for lightweight concrete and structural components [32]. Despite these advantages, the specific application of CVS for subsurface water storage remains unexplored. No study has experimentally evaluated the hydraulic behavior of CVS as a medium for storing water. Therefore, the lack of systematic research on its hydraulic properties represents an important gap that needs to be addressed.

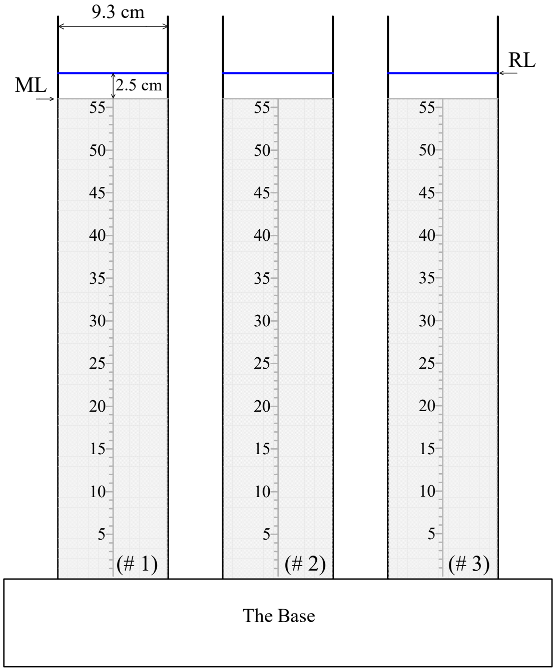
In this study, the water storage capacity of CVS with different particle sizes was evaluated using a fixed-volume cylinder test. For context, the results were compared with those of CG and natural sand under the same laboratory conditions. In addition to water retention, the current work examined the packing characteristics of these materials and compared their dry density. Together, these measurements provide a direct assessment of storage efficiency across the three material types and help determine whether CVS can serve as a potential medium for subsurface water storage.

II. METHODOLOGY

A. Experimental Setup

A fixed-volume cylinder test was conducted to compare the water storage capacities and dry densities of the CVS, CG, and natural sand. The materials were tested in different size ranges. The results were expressed as WSC% and dry density (kg/m^3). This was achieved through a structured experimental setup, controlled laboratory procedures, and quantitative data analysis. A transparent acrylic cylinder was used as the test chamber. Figure 1 shows the schematic of the experimental setup. The cylinder had an inner diameter of 9.3 cm and a height of 56 cm, providing an internal volume of about 3804.03 cm^3. The cylinders were open at the top to allow material placement and water addition, while the bottoms were sealed securely to prevent leakage and ensure correct measurements.

The transparent walls allowed for the direct observation of water movement and saturation during testing. A flat, stable platform supported the cylinder in a vertical position throughout the experiment.



☐ Tested Materials (CVS, CG, or Sands)

(#1), (#2) & (#3) Acrylic Cylinder

ML: Materiale Level at 56 cm

RL: Reference Level at 58.5 cm

Fig. 1. Schematic of the experimental setup.

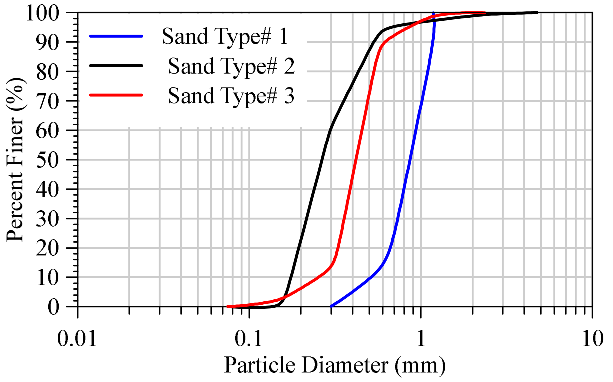


Fig. 2. Grain size distribution curves of the three sand types used in the experiments (determined according to ASTM C136/C136M – 19).

Three material types were examined: CVS, CG, and natural sand. For CVS and CG, the samples were divided into three particle size groups: 16–12.5 mm, 12.5–9.5 mm, and 9.5–4.75 mm. For sand, three types with distinct grain-size distributions were analyzed, as illustrated in Figure 2. The grain size characteristics were determined using the parameters D_{10}, D_{30}, and D_{60}, from which the coefficient of uniformity ($Cu = D_{60}/D_{10}$) and coefficient of curvature ($Cc = (D_{30})^2 / (D_{10} \times D_{60})$) were calculated. Sand type #1 (Cu = 1.84, Cc = 1.13) and sand type #2 (Cu = 1.76, Cc = 0.86) are classified as poorly graded sands. Sand type #3 (Cu = 1.77, Cc = 1.14) exhibits a slightly coarser and more uniform gradation compared with the other two sand types.

B. Procedure

Each test followed the same sequence to ensure consistency and reproducibility. The materials were oven-dried at 105 ± 5 °C for 24 h in accordance with ASTM C136/C136M – 19 [33]. This preparation ensured that only the voids within the media absorbed water during the experiments. After drying, the selected material was poured into the acrylic cylinder, which was filled to a height of 56 cm without applying compaction, as displayed in Figure 3. This approach simulated natural settling and avoided artificially increasing the density. All experiments were conducted in the laboratory under controlled indoor conditions, with a room temperature close to 25±2 °C and a relative humidity of 45–55%.

Fig. 3. Photograph of the assembled test apparatus.

Water was added slowly to minimize air entrapment and ensure a uniform saturation of the material. The process continued until the water reached the designated reference level, positioned 2.5 cm above the material surface. Care was taken to avoid overflow and visible air bubbles so that measurements remained consistent across trials. Once the reference level was reached, the cylinder was covered to avoid evaporation, and the water surface was monitored for 2 h. Additional water was supplied if the water level dropped during this period. Monitoring at the reference level ensured reliable measurements, as direct observation at the material surface was difficult, particularly for CVS and CG, owing to their rough texture and irregular shape. The total weight of water needed to maintain the reference level was recorded. Each test was repeated three times for every material and particle size category. These conditions provide consistency for comparison but may not fully replicate field conditions such as variable temperature, solar radiation, or evaporation rates in arid environments. Therefore, future field testing is proposed to validate the laboratory findings under natural environmental conditions.

C. Data Analysis

The total weight of water (W_l) required to reach and maintain the reference level for 2 h was recorded. The weight of water between the surface of the material and the reference level (W_r) was also calculated. The net weight of water filling the voids within the material (W_{net}) was calculated as:

$$W_{net} = W_l - W_r \quad (1)$$

where W_l is the total weight of water required to reach the reference level (g), W_s is the weight of water above the material surface to the reference level (g), and W_{net} is the net weight of water filling the voids within the material (g). This value was then converted to volume to obtain the WSC of the medium. The WSC% was then calculated by normalizing WSC against the total cylinder volume, according to (2). This ratio expresses the efficiency of each medium in storing water relative to the available space:

$$WSC\ \% = \frac{WSC}{V_t} \times 100 \quad (2)$$

where V_t is the internal volume of the cylinder (m^3).

The dry density of each material was calculated for each trial using:

$$\rho_d = \frac{M_s}{V_t} \quad (3)$$

where ρ_d is the dry density (kg/m^3) and M_s is the oven-dry mass of solids (kg).

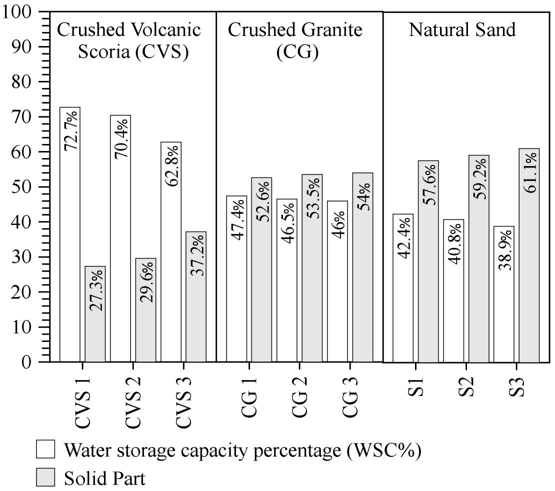
Dry density provided insights into the packing structure and void distribution of each material. Together, the values of WSC% and dry density were used to evaluate and compare the hydraulic performance of CVS, CG, and sand.

III. RESULTS AND DISCUSSION

The experimental results were presented and analyzed to assess the WSC% and dry densities of the CVS, CG, and sand. Focus was given on the influence of particle size, structure, and material properties on storage efficiency. Furthermore, the applicability of CVS for subsurface water storage in arid environments was outlined.

A. Water Storage Capacity

The results showed clear differences in the WSC% across the tested materials. As illustrated in Figure 4, CVS achieved the highest storage values, ranging from 72.7% to 62.8%. CG performed lower, with values between 47.4% and 46.0%, whereas sand recorded the lowest values, ranging from 42.4% to 38.9%. Table I summarizes the measured WSC% values for CVS, CG, and sand for different particle sizes. The consistency among replicate readings showed a variation of less than 2% for WSC%, confirming acceptable repeatability and measurement accuracy. These findings confirm that CVS provides greater void space and higher retention potential than CG and sand.



CVS 1:(16- 12.5 mm), CVS 2: (12.5- 9.5 mm), CVS 3:(9.5- 4.75 mm)
CG 1:(16- 12.5 mm), CG 2: (12.5- 9.5 mm), CG 3: (9.5- 4.75 mm)
S1, S2, S3: Sand Types

Fig. 4. WSC% of CVS, CG, and three types of sand.

TABLE I. SUMMARY OF WSC% AND DRY DENSITY VALUES FOR CVS, CG, AND SAND FOR VARIOUS PARTICLE SIZES

Material	**Particle size (mm)**	**WSC %**	**Dry density (kg/m^3)**
CVS # 1	16–12.5	72.7	404.3
CVS # 2	12.5–9.5	70.4	423.2
CVS # 3	9.5–4.75	62.8	500.8
CG # 1	16–12.5	47.4	1532.8
CG# 2	12.5–9.5	46.5	1541.5
CG # 3	9.5–4.75	46.0	1554.0
Sand # 1	See Figure 2	42.4	1468.7
Sand # 2	See Figure 2	40.8	1497.1
Sand # 3	See Figure 2	38.9	1528.7

The superior performance of CVS can be linked to its geological and structural features. Figure 2 portrays the grain size distribution of the sand types, which show fine particles and compact gradations that reduce voids and limit water storage capacity. Figure 5 presents the physical differences in the shapes of the tested materials. CVS are vesicular gravels containing internal voids formed during cooling. These vesicles enhance intraparticle voids, while irregular external surfaces increase interparticle void spaces. In contrast, the CG consists of dense crystalline minerals with smooth surfaces. This structure of CG leaves minimal porosity within the gravel body and reduces the void space between particles. A size-related trend was also evident in the CVS samples. The coarser fraction (16–12.5 mm) had the highest WSC% of 72.7%. The medium fraction (12.5–9.5 mm) recorded 70.4%, while the finer fraction (9.5–4.75 mm) showed a slightly lower value of 62.8%. This reduction is attributed to the tighter packing of smaller particles, which decreases the interparticle voids and limits the water storage efficiency. In comparison, CG showed minimal variation across the size groups, ranging from 47.4% to 46.0%, which aligns with its dense structure and low porosity. These results emphasize that both particle size and material structure strongly influence water storage performance.

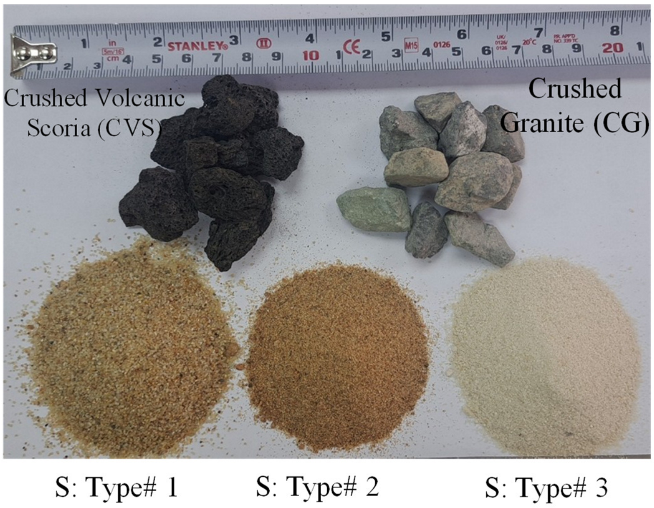


Fig. 5. Comparative photographs of CVS, CG, and the three types of sand, illustrating their differences in surface texture and particle shape.

B. Dry Density and Material Packing Characteristics

The dry density results show clear differences among the tested materials, as illustrated in Figure 6. The reported dry density values represent the mean of three replicates, with a variation of ±5 kg/m^3. Table I summarizes the measured dry density values for the different particle sizes. CVS recorded values between 404.3 and 500.8 kg/m^3. The CG recorded values between1532.8 and 1554.0 kg/m^3, indicating that CVS is approximately 70% lighter than CG. The sand showed similarly high values between 1528.7 and 1468.7 kg/m^3. These findings confirm that CVS is much lighter than CG and sand. Authors in [34] used coarse volcanic scoria as aggregate in concrete and reported bulk densities of 762 kg/m^3 in loose conditions and 860 kg/m^3 in the rodded condition. These values are notably higher than those obtained in the present study. The difference can be attributed to the aggregate characteristics: volcanic scoria employed in concrete applications typically has a well-graded particle distribution, which reduces void ratios and consequently increases density. In contrast, the CVS examined in this study consisted of uniform particle sizes (16–12.5 mm), (12.5–9.5 mm), and (9.5–4.75 mm). Such uniform gradation results in a higher void ratio, thereby leading to lower bulk density values compared to previous studies that considered scoria aggregates with better gradation for concrete production.

The packing behavior further explains these differences. CVS, with irregular shapes and rough surfaces, tends to form arrangements that preserve larger interparticle voids. In contrast, CG has smoother and more uniform surfaces, which encourage tighter packing and reduce the available void space. These findings confirm the link between particle geometry, dry density and water storage efficiency while also indicating that CVS is a suitable material for subsurface storage in arid regions.

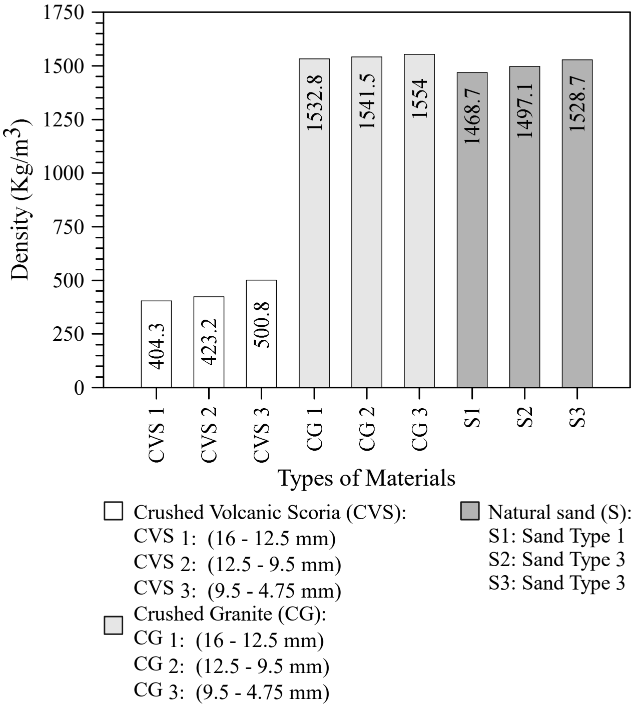


Fig. 6. Dry density results of CVS, CG, and three types of sand.

C. Practical Implications

CVS shows strong potential as a medium for subsurface water storage. When buried or covered, it minimizes evaporation losses by shielding the stored water from direct sunlight and wind. This property enhances long-term retention, making CVS particularly suitable for harsh desert climates. Its lightweight structure also improves practicality for decentralized applications. The material can be transported and installed with minimal equipment, reducing costs and infrastructure requirements. This advantage makes CVS a feasible option for rural and remote communities where conventional steel and concrete storage tanks are expensive or impractical.

The laboratory procedure developed in this study provides a simple and reproducible approach to evaluate porous storage media of CVS, CG, and sands. The proposed method can be scaled up to design modular and low-cost systems tailored to the local water needs. Such systems can strengthen water security in off-grid settlements while reducing dependence on costly desalination and conventional reinforced storage systems. These findings highlight CVS as a technically effective and economically viable material for sustainable water storage. Its combination of high porosity, low density, and broad availability positions it as a practical solution for managing scarce water resources in arid environments.

IV. CONCLUSIONS

This study experimentally evaluated Crushed Volcanic Scoria (CVS) as a subsurface water storage medium and compared its performance with that of Crushed Granite (CG) and natural sand under controlled laboratory conditions. Using a fixed-volume cylinder test, the Water Storage Capacity percentage (WSC%) and dry density of each material were measured to assess their hydraulic and physical characteristics. The results demonstrated that CVS consistently achieved the highest water storage efficiency due to its vesicular structure and irregular particle geometry, which enhance porosity and void connectivity. CVS also exhibited significantly lower dry density, confirming its lightweight and highly permeable nature compared to CG and sand.

Overall, CVS stored approximately 22% more water than CG and 30% more than sand, highlighting its potential as a technically effective and economically viable material for subsurface water storage in arid regions. These findings address a key research gap and provide the first experimental evidence supporting the use of volcanic scoria as an alternative to traditional storage materials.

While the laboratory results are promising, the study is limited to controlled indoor conditions. Field-scale validation is needed to confirm CVS performance under real environmental conditions, including temperature fluctuations, and long-term durability. Future research should examine water quality interactions, such as potential changes in pH, ionic concentration, and trace metals, during prolonged water contact. In addition, further studies are proposed to evaluate hydraulic parameters, such as the void ratio, porosity, degree of saturation, and permeability, to provide greater understanding of CVS behavior. Economic assessments comparing CVS-based systems with conventional steel and concrete tanks will also be valuable for determining cost-effectiveness and practical feasibility.

Future applications may include the integration of CVS storage systems with rainwater harvesting, artificial recharge, and soil aquifer storage techniques, which can enhance groundwater sustainability and reduce the reliance on energy-intensive desalination.

In conclusion, CVS is a locally available, lightweight, and sustainable material for subsurface water storage in arid regions, such as Saudi Arabia. Its unique structural properties allow greater water retention with minimal infrastructure and cost, making it particularly suitable for rural communities, agricultural use, and off-grid settlements. The use of CVS contributes to decentralized and sustainable water management, offering a practical solution to enhance water security and advance national sustainability goals.

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