Impact of Crushed Peruvian Scallop as filler on the Properties of Pervious Concrete Mixtures

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Abstract

The use of pervious concrete with crushed Peruvian scallop seashell waste (CSS) emerges as a sustainable solution to two significant issues in Piura. It enhances waste management in the aquaculture sector in Sechura by reducing waste accumulation and helps mitigate flooding caused by events such as "El Niño". This research evaluates the behaviour of pervious concrete incorporating CSS as a filler with a particle size smaller than 75 µm. The experimental programme comprised two phases. In the first phase, the fresh state characteristics of the cement matrix with CSS filler were analysed. A standard paste was utilised, and various formulations were designed by adjusting CSS percentages (5%-15%) and plasticising admixture (0%-1.4%), while maintaining consistent matrix volume and water-cement ratio. In the second phase, matrix compositions with similar coating thicknesses to the standard paste were selected to produce pervious concrete, according to ACI 522-2023 guidelines, with a water-cement ratio of 0.35 and high compaction energy. Results indicate that incorporating CSS filler increased the compressive strength of pervious concrete by up to 24% at 28 days for a 10% CSS content, while maintaining permeability rates above 20 mm/s.

Keywords

Pervious concrete, Peruvian crushed scallop shell, Compressive strength, Permeability.

1. Introduction

There is an urgent need to seek alternatives to address the environmental problems generated by the construction industry. This industry is responsible for 30% of global carbon dioxide (CO_2) emissions and consumes approximately 3000 tons of raw materials per year (Pacheco-Torgal & Jalali, 2012; Silva et al., 2020). Such significant environmental impacts underscore the importance of adopting sustainable practices and finding innovative ways to utilize waste materials.

Currently, the district of Sechura, Peru, is one of the main producers of scallop seashells, representing 80% of the national production and 50% of the production in South America. This activity generates approximately 100,000 tons of shell waste annually, which is disposed of in authorized landfill (Poicon Rivas, 2014). Although current regulations ensure these residues are clean upon arrival at the landfill, the disposal issue persists due to the space they occupy. In recent years, it has been found that Peruvian crushed scallop seashells (CSS) can be used as construction material, providing an alternative that helps mitigate the above-mentioned problems (García & Guerrero, 2020; Martinez-Agurto, 2019; Rivas Granizo, 2019; Santamaria, 2020; Varhen et al., 2017).

Pervious concrete, an eco-friendly material, is characterized by a high volume of connected pores and good water permeability (Deo & Neithalath, 2010; Schaefer, 2006; Tennis et al., 2004; Zhong et al., 2018). This material has gained significant interest due to its ability to allow water to pass through its structure, making it a highly effective solution for controlling stormwater runoff. Additionally, pervious concrete can help mitigate issues such as the urban heat island effect, tire-pavement interaction noise, groundwater depletion, and traffic safety (Haselbach et al., 2011; Olek et al., 2003; Zhong et al., 2018).

The incorporation of Peruvian scallop seashells in pervious concrete has been minimally studied. (Nguyen et al., 2013a) confirmed that crushed seashells (particle size between 2 and 4 mm) can be used to produce pervious concrete with properties like those of standard samples. However, in the case of CSS, it has been found that using it as filler in sizes smaller than 75 µm can enhance concrete properties (García & Guerrero, 2020). Other studies (Nguyen et al., 2013b; Nguyen et al., 2013a, Nguyen et al., 2017) have shown that adding crushed shell waste can influence both the fresh and hardened states of concrete, including workability, unit weight, air content, compressive strength, flexural strength, porosity, and permeability. This study aims to evaluate the potential use of Peruvian crushed scallop seashells (CSS) from Sechura, Piura as filler in pervious concrete, contributing to mitigating flood effects caused by rain and providing an effective waste management solution.

2. Materials and methods

2. 1 Cement and plasticizer

The Type I cement from the "QHUNA" brand was employed. Its chemical composition primarily consists of CaO (65.20%) and SiO_2 (20.40%). Regarding its physical properties, it exhibits a specific surface blaine of 3620 cm^2g^{-1}, density of 3.14 g/ml and initial setting time of 122 min.

The plasticizer (SP) used is SikaCem, a liquid admixture composed of lignosulfonates and organic polymers, specifically designed for producing mortars and flowing concrete. Its incorporation into the mixture enhances the workability of concrete, facilitating placement and compaction, especially in the presence of filler.

2. 2 Coarse aggregate and seashell waste

Quartzite intrusive crushed gravel (G) processed from river stone from rocks of the Andes with a size particle between of ½ in and 3/8 in (75% and 25%, respectively), a specific gravity of 2770 $kg.m^{-3}$, loose unit weight of 1403 $kg.m^{-3}$, rodded unit weight of 1495 $kg.m^{-3}$, an absorption coefficient of 0.95% and a water content of 0.63 %.

The CSS was sourced from "Congelados Piura Seafood SAC," located in Sechura. It was confirmed that the waste material was devoid of organic content, following a thorough cleaning process conducted at the aforementioned facility. The crushing of Peruvian scallop seashell was conducted using a screw mill available at the Laboratory of Construction Materials Testing (LEMC) at University of Piura (UDEP). This process proceeded in two stages. Initially, a pestle was employed to reduce the original material size to approximately 3 cm before further processing in the screw mill. Pre-set, the mill reduced the material to dimensions smaller than the No. 16 mesh sieve. To obtain CSS particles smaller than 75 µm, wet sieving was performed using the No. 200 mesh sieve. Their particle size distribution, as presented in Fig 1. The figure highlights significant size differences between this filler and the coarse aggregate. The average particle size of this material is 12.8 µm. Chemical composition of CSS is mainly CaO (53.70 %).

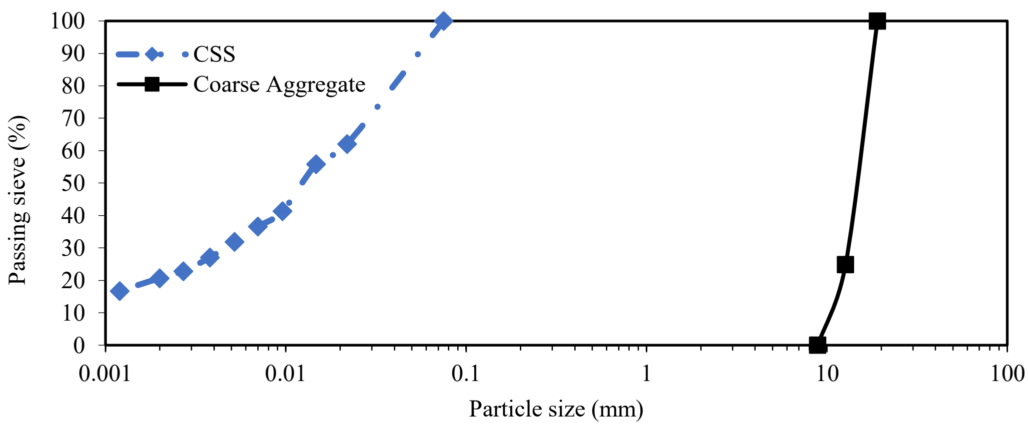


Fig 1. Particle size distribution of coarse aggregate and crushed seashell (CSS).

2. 3 Concrete mix design and test variables

In the Stage I, the fresh state characteristics of the paste (cement, water, CSS, and plasticizer) were studied using Ideal Thickness Paste (IPT) and Actual Thickness Paste (APT). Four CSS percentages (0, 5, 10, and 15% by weight of cement) were defined, along with the percentage of SP to be used (0, 0.20, 0.40, 0.60, 0.80, 1.00, 1.20 and 1.40 %). In the Stage II, the hardened state of permeable concrete (cement, water, coarse aggregate, CSS, and SP) was studied through compressive strength and permeability tests. For all mixtures, the amount of cement and water was adjusted to maintain consistent paste volume and water-cement ratio (0.35). Table 1 shows the mix design for stage II, respectively.

Table 1. Mix designs for Stage II.

Component (kg.m^{-3})	0% CSS 0% SP (Control Mix)	5% CSS 0.4% SP	10% CSS 0.6% SP	15% CSS 1.2% SP
Cement	348.9	339.2	329.6	320
Water	126.8	123.4	120	116.6
CSS	0	17.4	34.9	52.3
Coarse Aggregate	1462.8	1462.8	1462.8	1462.8

Ideal Paste Thickness (IPT) measures the adhesive capacity of the cement paste. This property is quantified by measuring the thickness formed around a standard vertical surface (Jimma & Rangaraju, 2014). The following formula is used to calculate the ideal paste thickness:

$$IPT\ (mm) = \frac{m_p}{\rho_p * \pi * d * L} \times 10^3 \quad (1)$$

Where:
IPT = ideal paste thickness (mm).
m_p = mass of paste in the pipe (g).
ρ_p = paste density (g.cm^{-3}).
d = pipe diameter (mm).
L = length of the pipe covered by paste (mm).

Actual Paste Thickness (APT) evaluates the ability of the cement paste to generate a stable film on the aggregate surfaces, while providing an indirect measure of its bonding capacity and the amount of paste required to coat the aggregate particles. The effectiveness of this test is affected by the surface condition and moisture content of the aggregate (Jimma & Rangaraju, 2014; Xie et al., 2018). The following formula is used to calculate the actual paste thickness:

$$APT\ (mm) = \frac{M_p}{M_a * \rho_p * S_a} \times 10 \quad (2)$$

Where:
APT = real paste thickness (mm).
M_p = mass of cement paste adhered to the aggregate (g).
M_a = mass of aggregate in SSD condition (g.cm^{-3}).
ρ_p = paste density (g.cm^{-3}).
S_a = specific surface area of the aggregate (cm^2.g^{-1}).

Cylindrical specimens of ϕ100 mm x 200 mm were prepared to evaluate permeability and compressive strength (ASTM C09 Committee, 2016) at 7-day stage and 7 and 28 day stages, respectively. All specimens were removed from the mold after 24 h and were wet cured in a water chamber at 23 ± 2 °C until the testing date.

Permeability is the ability of concrete to allow water to flow through its pores and can be assessed by means of a variable load permeameter, the design of which was proposed by (Olek et al., 2003) and is mentioned in the most recent ACI report (ACI American Concrete Institute Committee 522, 2023). A permeameter was developed according to the recommendations of both reports (See Fig 2). The permeameter is mainly composed of properly assembled pipes, fittings and a valve. The test starts by pouring water from the top of the acrylic tube until the water overflows the drain pipe, with the valve in the open position. At this point, the system is fully saturated and the valve is closed. Water is then poured until the water column in the acrylic tube reaches 350 mm. Carefully open the valve and, using a stopwatch, record the time it takes for the water level to drop from the initial 350 mm to 130 mm. With the data collected, the permeability value is finally calculated using the following formula:

$$K = \frac{A_1 h}{A_2 t} \ln\left(\frac{h_i}{h_f}\right) \quad (3)$$

Where:
A_1 = cross-sectional area of acrylic tube (cm^2).

A_2 = cross-sectional area of concrete sample (cm^2).
h = sample length (cm).
h_i = height of water level before drainage (cm).
h_f = height of water level after drainage (cm).
t = time taken for the water level to go from h_i to h_f (cm).

(a) (b)

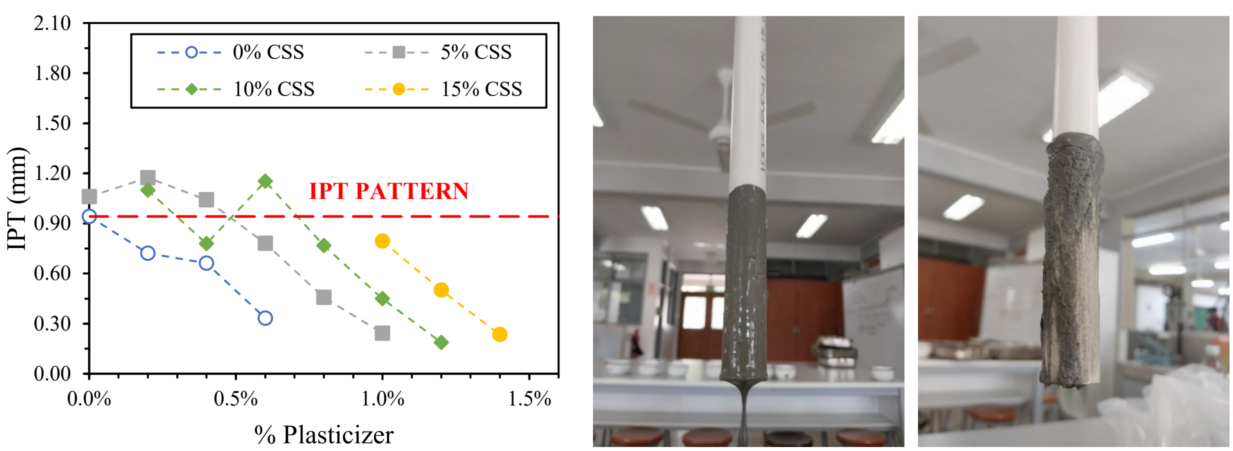
Fig 2. (a) Permeameter and (b) Permeable concrete specimens for permeability test.

3. Results and discussion

3. 1 Fresh state analysis (Stage I)

The results of Ideal Paste Thickness (IPT) are presented in Fig 3. Values not recorded in the figure correspond to matrices that were either excessively fluid or viscous, indicating they failed to spread or cover the surface of the PVC pipe pieces uniformly. This behaviour suggests that the coating on the aggregates would be similar.

Fig 3 indicates that up to 5% CSS addition is feasible without the need for an SP. Beyond this percentage, the matrix becomes so viscous that it hinders the formation of a continuous and uniform thickness. Therefore, for CSS proportions greater than 5%, the inclusion of a SP becomes essential to improve the dispersion of the filler within the binder matrix, facilitating the spread of the matrix over the PVC pipe surface. This phenomenon occurs due to the reduction in matrix viscosity, ensuring good adhesive capacity.

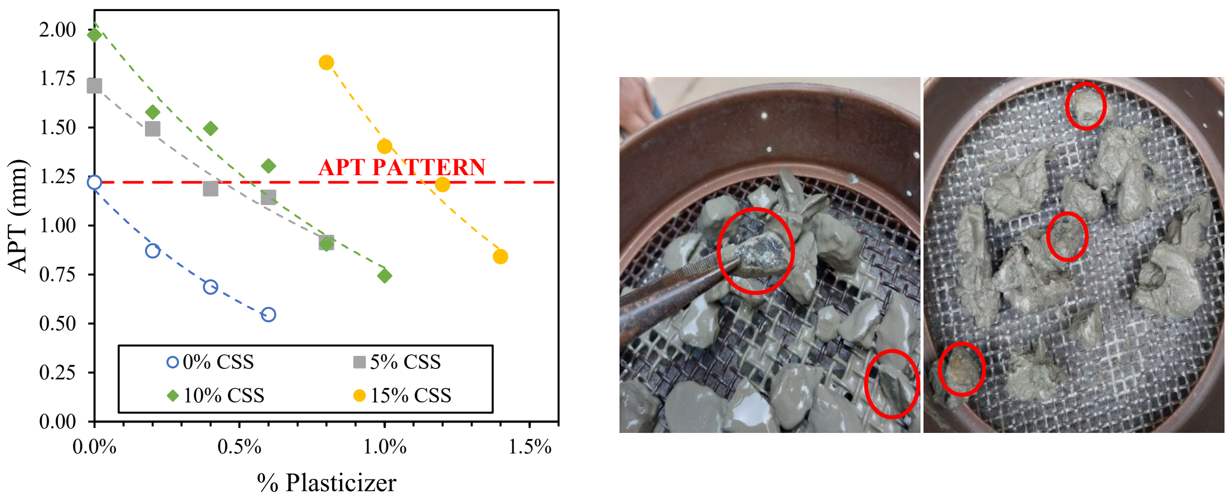


(a) (b) (c)

Fig 3. (a) Results of Ideal Paste Thickness (IPT), (b) Excessively fluid matrix and (c) Excessively viscous matrix.

The results of Actual Paste Thickness (APT) are presented in Fig 4. Values not recorded in the figure correspond to matrices that were either excessively viscous, resulting in an uneven distribution around the aggregates, or excessively fluid, causing them to drain off the aggregate surface after the compaction process, leaving some particles partially uncovered. The exact thickness of the standard paste is represented by a dotted line to facilitate comparison with other formulations.

The APT can be attributed to the amount of matrix added to the mix, provided that the matrix has high viscosity. In such cases, the matrix tends to adhere better to the aggregates, forming a thicker, though not always homogeneous, layer. Conversely, when the matrix is excessively fluid, the amount of matrix should be minimal to ensure coverage of all particles. In this scenario, adding more binder matrix does not increase thickness but simply causes it to drain to the bottom. Furthermore, varying the CSS content from 5% to 10% does not result in a significant change, as the values are very close to each other. The trend also shows that as the SP content increases, the thickness tends to decrease, whereas for the same SP dosage, the thickness increases with higher CSS content.



(a) (b) (c)

Fig 4. (a) Results of Actual Paste Thickness (APT), (b) excessively fluid matrix and (c) excessively viscous matrix.

3.2 Hardened state analysis (Stage II)

The matrix formulations selected for Stage II were those that exhibited a coating thickness on the aggregates similar to that of the control mix. The selected formulations included: 5% CSS with 0.4% SP, 10% CSS with 0.6% SP, and 15% CSS with 1.2% SP. The reason for this selection is based on previous research on stage I, demonstrating that coating thickness significantly affects the porosity and other mechanical properties of pervious concrete. Therefore, to isolate and evaluate the influence of CSS, the coating thickness was kept constant while only the amount of CSS was varied.

The results of the compression strength tests are presented in Figure 5. Incorporating CSS into the control pervious concrete mix enhanced its compressive strength. While the compressive strength of the control mix at 28 days was 9.6 MPa, mixtures with CSS showed values ranging from 11 to 11.9 MPa. This improvement is primarily due to CSS's role as an inert filler, composed mainly of calcium carbonate, which contributes to denser packing within the concrete matrix by promoting the formation of additional cement hydration products(Zaetang et al., 2017). In contrast, other supplementary cementitious materials such as silica fume and fly ash have varying effects on compressive strength. Silica fume, when used up to 5.5%, not only improves compressive strength but also enhances resistance to freeze-thaw cycles (Adil et al., 2020), while excessive substitution with fly ash can lead to a significant reduction in strength (Aoki et al., 2012). Additionally, nano-silica can increase strength without negatively impacting the void ratio and permeability (Mohammed et al., 2018). Beyond compressive strength, supplementary materials like silica fume have been shown to improve fatigue resistance, thereby increasing durability against freeze-thaw cycles (Chen et al., 2013), and they are known to enhance adhesion within the cement paste (ASTM C09 Committee, 2020).

However, the effects of CSS on these other properties, such as freeze-thaw resistance and adhesion, have not yet been fully explored and warrant further investigation.

Additionally, there exists an optimal level of CSS addition, situated between 5% and 10%. Beyond this range, compressive strength began to decrease. The enhancements in strength for samples with 5% and 10% CSS surpassed those with 15% CSS. For instance, concrete containing 5% CSS exhibited a 21.9% increase in compressive strength at 28 days, while concrete with 10% CSS experienced a 24% increase. In contrast, concrete with 15% CSS only showed a 14.6% strength increase over the same period compared to control pervious concrete mix. Furthermore, it was observed that standard concrete achieved approximately 75% of its 28-day strength at 7 days, whereas mixtures containing CSS attained between 75% and 90% of their 28-day strength during the same period.

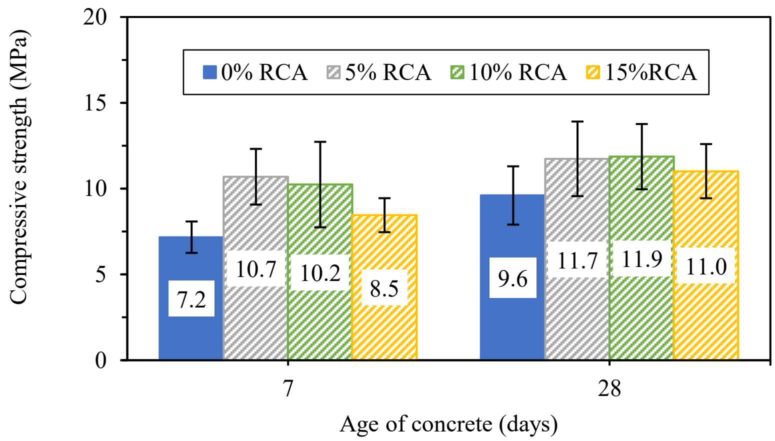


Fig 5. Results of compressive strength test.

Fig 6 presents the permeability test results, where all formulations exhibit higher permeability than the control mix of pervious concrete. The highest permeability observed was for the concrete containing 5% CSS and 0.4% SP, achieving 29.5 mm/s, which is 76.6% higher than the control mix of pervious concrete (16.7 mm/s). This increase is likely attributed to the uniform distribution of CSS throughout the cement matrix, which enhances the pore interconnectivity. Additionally, the fluid cement matrix formed a very smooth layer around the aggregates, which further facilitated the high velocity of water flow, thereby enhancing permeability.

As the percentage of CSS exceeds 5%, the permeability tends to decrease from the peak value of 29.5 mm/s; however, it remains 24.6% higher than that of the control mix. This variation can be explained by the increased influence of the CSS particle shape at higher quantities. The needle-like and irregular shape of CSS particles can impact pore distribution and connectivity, creating irregularities in the porous pathways through which water flows. This results in the water traversing a longer path, a phenomenon known as tortuosity.

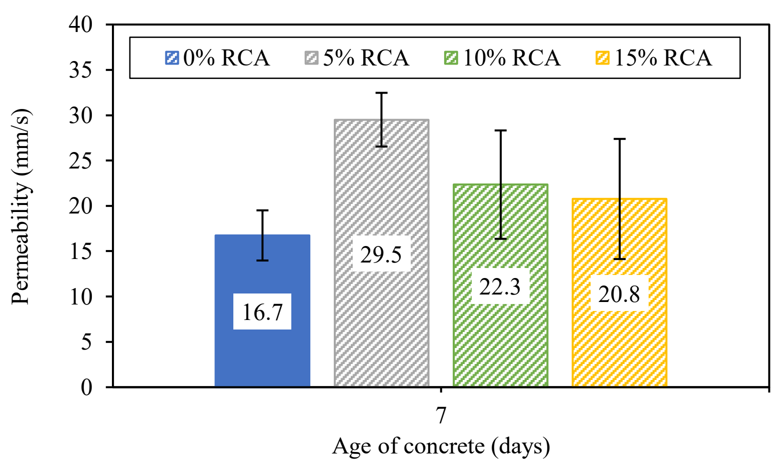


Fig 6. Results of permeability test.

4. Conclusions

The research findings present three key conclusions regarding the incorporation of Peruvian scallop crushed seashell (CSS) in pervious concrete formulations. Firstly, the study establishes an optimal CSS content range, noting that additions up to 10% significantly enhance both compressive strength and permeability. Beyond this range, however, diminishing returns are observed, with higher CSS percentages leading to reduced compressive strength and slightly lower permeability compared to the optimal levels between 5% and 10% CSS content. Despite this, even at higher CSS percentages, permeability remains greater than 16 mm/s, which exceeds the result of the control sample.

Secondly, the study underscores the critical role of SP admixtures when incorporating CSS above 5%. Without these additives, the cementitious matrix becomes excessively viscous, compromising uniform distribution and thickness coverage around the aggregates. This highlights the importance of maintaining appropriate workability while enhancing the material properties of pervious concrete with supplementary materials like CSS.

Lastly, the research emphasises the environmental and sustainability benefits of using CSS as a filler in pervious concrete. Unlike traditional supplementary materials such as fly ash or silica fume, CSS is chemically inert and sourced abundantly as a waste product. The research findings contribute valuable insights into optimizing CSS utilization in concrete mixes, supporting sustainable construction practices aimed at reducing environmental impact while improving.

Acknowledgements
This work was funded by CONCYTEC through the PROCIENCIA programme in the framework of the "E041-2023-02" contest, according to contract PE501082299-2023.

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