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Seashell as Aggregate in Cemented Materials: A Review

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Abstract The tendencies in the field of cemented materials are currently oriented towards the use of alternative products in cemented materials to reduce the strong dependence on natural resources. The materials most used for this purpose, are recycled ones coming from the waste discarded by the factories. One of these new methods consists of the use of mollusc shells as aggregate in ordinary concrete, cement mortar, pervious concrete, and mineral addition to cement. Experimental analysis has been conducted on the employment of molluscan seashells as a substitute for aggregates in cement materials. This document is a review of shell elaboration in cemented materials. The article first presents a summary of the preparation ways and overall properties of seashells. Then it discusses the existing applications within the construction sector. Mollusc shells generally have very variable geometries and shapes, also the granular distribution depends on the shell type and crushing process. Molluscan shells contain characteristic traces of chloride and sulfate salts. Although the addition of the shell aggregate reduces the physico-mechanical properties of the cemented material, the current understanding of the elaboration of those seashells requires additional analysis of numerous aspects of their behavior.

Keywords Seashell Aggregates, Ordinary Concrete, Pervious Concrete, Physical Properties, Mechanical Properties

1. Introduction

Seashells are one of the wastes that accumulate rapidly, especially in littoral zones and in regions that consume a lot of shellfish products. For instance, 17.5 million tons of shellfish are generated every year [1].

The global production of mollusks accounts for regarding 20% of the entire global aquaculture production [2] [3]. The most common marine mollusc species are bivalve molluscs. Approximately 88% of mollusc aquaculture is bivalve mollusks including 33% of clam (including arch and cockle), 31% of oyster, 12% of mussel, and 10% of pecten and scallop [4].

Shell waste, such as cockle shells, oyster shells, scallop shells, and mussel shells, is widely available in certain regions and is generally disposed of in garbage sites [3].

One of the most promising solutions to valorize seashell waste is to use it as aggregate in cemented materials. In littoral regions, people have already valorized seashells as aggregate for simple cemented structures [5] [6] [7]. Research projects on the effect of seashells as a substitute aggregate in cemented materials have been conducted for at least twenty years to verify the feasibility of a practical application. The use of these seashells as a recycled aggregate in cement materials shows the feasibility and durability needed. The authors also concluded that seashells are very economical in terms of price, compared to conventional aggregates [8].

The large quantities of shellfish in the littoral regions of the world indicate that seashells are proposed as a material that can partially replace aggregates in cemented materials. Therefore, seashells have the potential to be sources of aggregates required for cemented materials around seashell areas.

2. Seashell Characterization

2.1. Method of Preparation of Seashells

The seashell aggregates used in the cemented materials should be washed to eliminate both salts and organic matter. Impurities from the seashells have been eliminated without indicating the tactics for cleaning the seashells [9] [10].

The most usual cleaning method is to wash the seashells with water and dry them in the sun or air. Additionally, to washing, hand selecting of impurities was performed [11] or elimination of organic matter and other dirt with social brushes [12] has been done. Certain investigations subjected the shells to elevated heat for various lengths of time to dehydrate the seashells. The process consists of drying the seashells in an oven at 105 °C for 4 hours [5], and 50 °C for 24 hours [13].

2.2. Geometry, Shape, Crushing, and Granulometry of Seashell

Mollusc shells generally have very variable geometries depending on age and species. The dimensions of length and height are similar and about 7 cm for adult specimens. The shell thickness varies from 1 to 4 mm [14].

Flattened shell particles have a major specific surface area and their granular arrangement is less efficient [15]. Therefore, they require a very high amount of paste compared to rounded particles to achieve the same workability [16]. Nevertheless, angular particles can increase the mechanical strength of concrete [17] [18].

Some recommendations limit the amount of flaky and elongated shaped particles in concrete. Flattened shapes can be quantified by determining the flattening coefficient [19]. The coefficient of flattening for 4/6.3 mm crushed scallop shells was determined to be 96%, and for crushed scallops, it ranged from 90 to 98%. These values exceed the limits for all standards. Drying this coefficient classifies the gravels for concrete up to a content of flattened particles equal to 50% according to the standard NF EN 933-3. The British standard BS 812-105 does not allow the incorporation of several particles of flattened form greater than 40% of the total mass of aggregate. The Spanish concrete standard EHE-08 stipulates that the flattening coefficient must be less than 35% [20].

To reduce shell flattening, most research on incorporating marine shells into cementitious materials uses crushed shells. Crushing shells reduces shell flattening while generating highly variable particle size fractions, especially in finer sizes. Different types of crushers, such as the jaw crusher [21] [22] the drum compactor [23] and the hammer [12] have been used to grind the shells.

Shell type and crushing process influence granular distribution [24]. The seashells used as fine aggregate and coarse aggregate are of different sizes. In general, seashells used as coarse aggregate were not crushed or the particle size of the seashell aggregate was not reported [18]-[21]. The fine aggregate of seashells was crushed and sieved to sizes less than 5 mm. Crushed seashells used as coarse aggregate ranged from 10 to 20 mm [10] [29]. The maximum size of uncrushed seashell aggregate was generally 25 mm or less [9] [11] [25] [27].

2.3. Seashell Microstructure

In general, seashells are composed of nearly 90% of calcium carbonate $CaCO_3$ [30]. A part is composed mainly of aragonite. While other shells are formed mainly of calcite. However, authors have shown that shells could be composed of 30% aragonite and 70% calcite [31].

The structure of the shell is heterogeneous but very compact. By scanning electron microscope (SEM) observations, the authors identified three layers [2]. The inner layer seems to be formed by a simple transverse structure (), while the middle layer seems to be organized as a complex transverse structure. The outer layer is a very fine, deposit-like layer.

2.4. Chemical Composition

The calcium oxide content represents 35 to 54% by weight in the shell. Other elements are present in the shells: sulfur, sodium, magnesium, aluminum, silicon, strontium, iron, etc. Other elements are in very low concentration. These elements come from the external environment, from the organic matrix present around the solid $CaCO_3$ structure of the shell, or impurities [4]. The loss on ignition (LOI) of molluscan shells is close to values reported for other aggregates [32] [33] [34]. The loss on ignition of shells varies from 41 to 51% by weight [23].

2.5. Physical and Mechanical Properties

The texture, porosity, or specific surface area of shells are properties that vary by mollusc type but not only [2] [35] [36]. Some of their physical characteristics are a function of the size of the shell crushes. Thus, the density of crushed shells depends mainly on their composition but also the size of the crushed shells. Crushed mollusc shells have a bulk density between 500 to 1015 (kg/m^3), and a specific gravity varies between 1.85 to 2.73 (Table 1).

The water absorption of porous materials is defined as the amount of water required to fill their pores. Shells have a water absorption coefficient that also increases with the degree of crushing. The water absorption coefficient for mollusc shells varies between 0.1 to 12.99%. This implies that some of those seashells surpassed the maximum absorption value of 8% suggested by the ACI [37].

Table 1. Physical properties of mollusc shells [4]

Properties	Cockle	Oyster	Mussel	Scallop	Periwinkle
Thinness module	6.57	2.0-6.5	1.9-5.38	4.4-4.57	--
Specific gravity	2.09-2.64	1.85-2.48	2.62-2.73	2.5-2.64	2.05-2.07
Bulk density (kg/m^3)	--	--	--	1015	514
Compacted bulk density (kg/m^3)	1408-1420	--	--	1224	515-1353
Moisture content (%)	--	--	--	0.3	1.1-8.32
Water absorption (%)	0.1-2.5	2.9-9.2	2.17-4.12	1.88-3.65	9.03-12.99

Table 2. Mechanical properties of mollusc shells [4]

Properties	Cockle	Oyster	Mussel	Scallop	Periwinkle
Impact value of aggregates (%)	52.4-52.8	--	--	--	32.5
Aggregate crush value (%)	47.5-48.7	--	--	--	59.6
Abrasion value of aggregates (%)	15.8	--	--	--	--
Los Angeles Coefficient (%)	--	--	20	--	45.73

The resistance to fragmentation of the crushed shells is determined in general via the Los Angeles test, according to NF EN 1097- 2. The Los Angeles coefficient of the shells varies between 20 to 45.3. These values lower than 30 classify the mussel shells in category A. Therefore, they are quite resistant to fragmentation, according to the NF P 18-545 standard. The aggregate crush value, aggregate impact value, and aggregate abrasion value that measure toughness are presented in Table 2.

3. Current Valorization of Seashell Co-Products in the Cemented Materials

Several scientific studies have investigated the incorporation of shells into cemented materials [2] [19] [25] [40] [41]. In general, the shells used were crushed. [25] as well as [9] have investigated the use of uncrushed periwinkle shells in concrete. In all these studies, the shells were used as partial replacements to the total of gravel, and sand and as cemented addition. [42] has also studied draining concretes based on crushed scallop shells of size 2/4 and 4/6.3 mm.

3.1. Ordinary Concrete: Gravel Replacement

Researchers have been interested in the replacement of natural gravel with seashells in concrete [5] [2] [25] [29]. These researchers reported that the replacement of gravel with raw shells substantially decreases the workability as well as the density and consequently the mechanical properties (Figure 1).

At the incorporation of 20% crushed scallop shells, the fresh density and 28-day compressive strength remain similar or slightly lower [35]. [43] find an average decrease in density between 27 and 35% and compressive strength -9% for 20% incorporation of cockle shells (Figure 2).

Other researchers incorporated crushed mussel shells into concrete. They found that the replacement rates of natural aggregate by mussel shells should be limited to 25% for gravel and 12.5% for sand and gravel together. With these replacement rates and heat treatment at 135°C for 30 minutes, mussel shells can be used as aggregate in ordinary concrete [2].

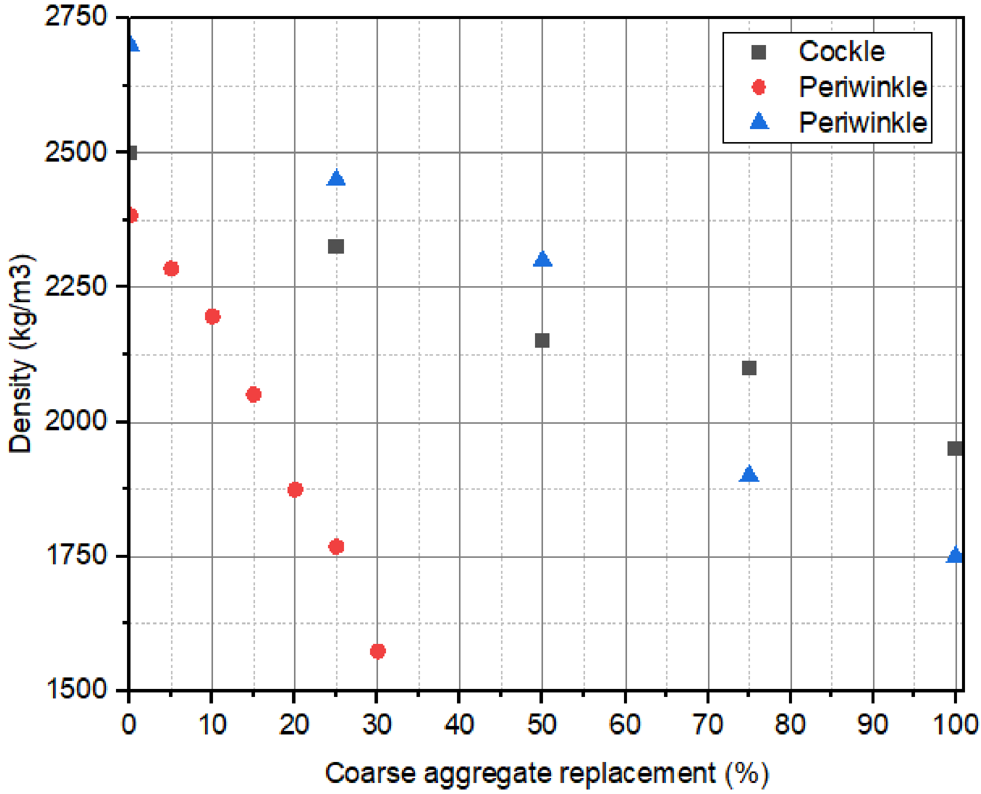

Figure 1. Density at 28 days of fresh seashell-based concrete

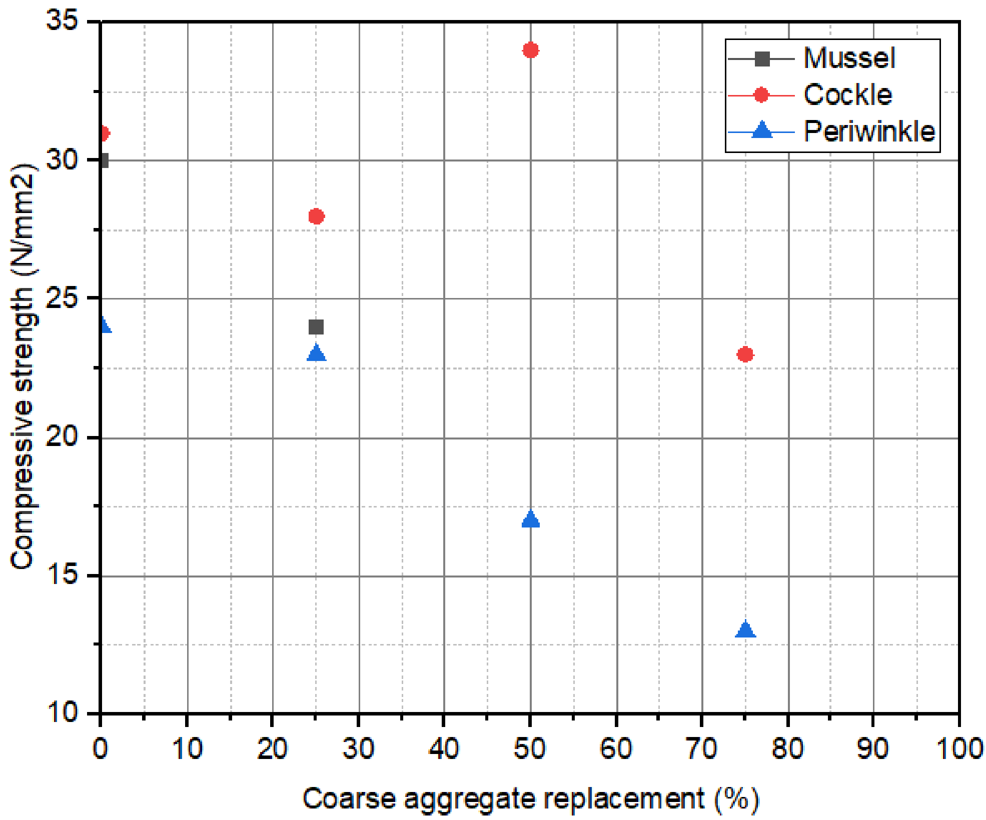

Figure 2. 28-day compressive strength of seashell-based concrete

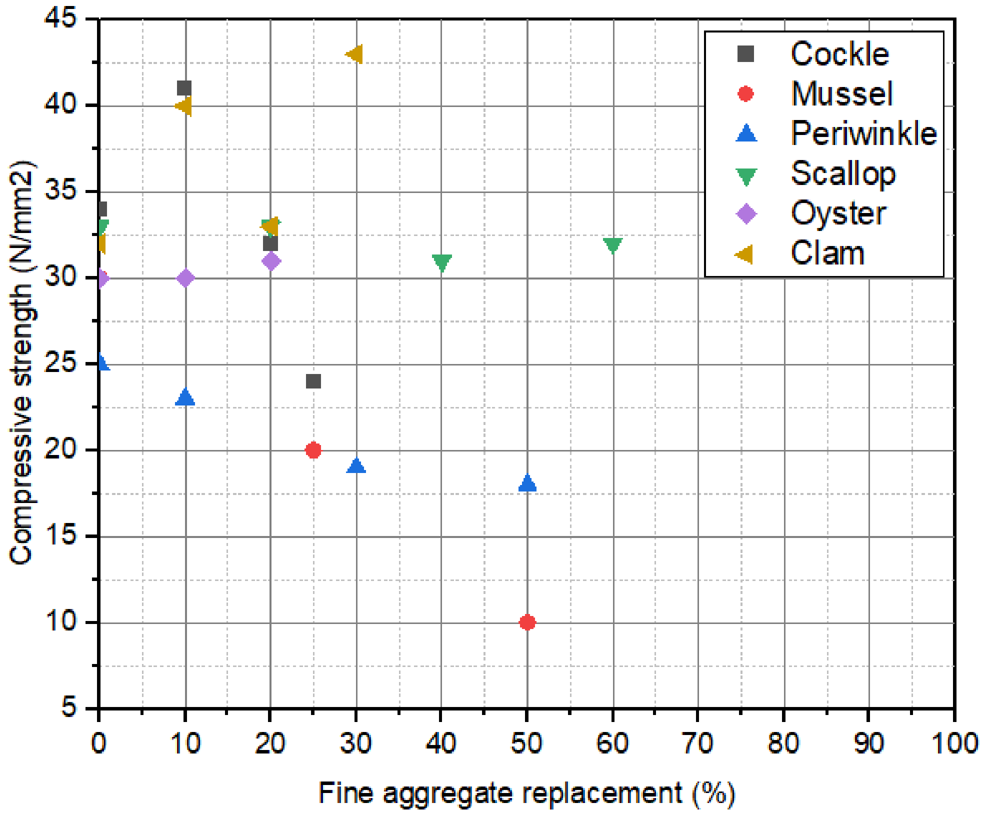

Figure 3. 28-day compressive strength of shell-based concrete

3.2. Ordinary Concrete: Replacement of Sand

Methods for incorporating shells in place of sand in concrete are varied. Some authors have proposed the replacement of the sandy fraction of the concrete with oyster shells of the same size as the replaced sand (0/5 mm) but with a very different granular distribution [44]. Subsequently, [33] replaced the sand with shells of similar size and modulus of fineness. This means that granulometry is not the determining factor in the resulting properties. [35] replaced natural fine aggregate with mussel shell sand by employing four replacement ratios, 0%, 25%, 50%, and 65%. These literature results are presented in Figure 3.

3.3. Cement Mortar: Replacement of Sand

Other researchers have devoted themselves to the incorporation of shells into cement mortars. [45] and [19] have formulated mortars of composition that are proposed by the standard NF EN 196-1. [46] have studied a mortar that is rich in fines, while [47] have focused their research on low-strength mortars with low cement dosages (160 $kg.m^{-3}$). [24] and [48] have tested multiple compositions, which allows them to determine the impact of the formulation on the properties of the mortar.

3.4. Mineral Addition for Cement

A few authors have incorporated powdered crushed shells into the matrix of cemented materials [6] [19], [44], [48] [49]. Intending to use the shells as a cement additive, these authors found no disturbance in the hydration of the cement. The shell powder integrates perfectly into the matrix of the cemented materials, so it probably plays a filling role as an inert material [7].

3.5. Pervious Concrete: Replacement of Gravel

Apart from the use of shells in ordinary concrete as aggregates, [50] and [51] were interested in the use of scallops and oyster shells to replace gravel in pervious concrete. In Sugiyama's work, 50 and 100% of the gravel are replaced by scallops of 5/25 mm granular class. Pervious concrete has very low strength and a significant decrease in strength is observed when the proportion of shells increases. At the same time, the void volume is almost doubled when all the gravel is replaced by the shells.

[52] explored the possibility of making porous concrete based on crushed scallops. Replacing the 5/15 mm gravel with the 5/25mm crushed scallops results in a large increase in the porosity of the concrete and thus strength losses. As the porosity increases from 28.1 to 43.1%, the compressive strength decreases from 10.6 to 1.9 MPa. (Figure 4 and Figure 5).

[51] also showed that the use of crushed oysters of granular class 0.35/40 mm as gravel (total substitution) led to the obtaining of pervious concrete with very high

permeability, but with very low mechanical performances. In addition, this author showed the negative influence of the vibratory compaction method on the characteristics of pervious concrete. Although the number of tests and the number of samples is limited and some results are difficult to interpret, [51] confirms that crushed oysters can be a strong aggregate and that the development of pervious concrete from this type of shell is possible, provided that an appropriate compaction method is applied.

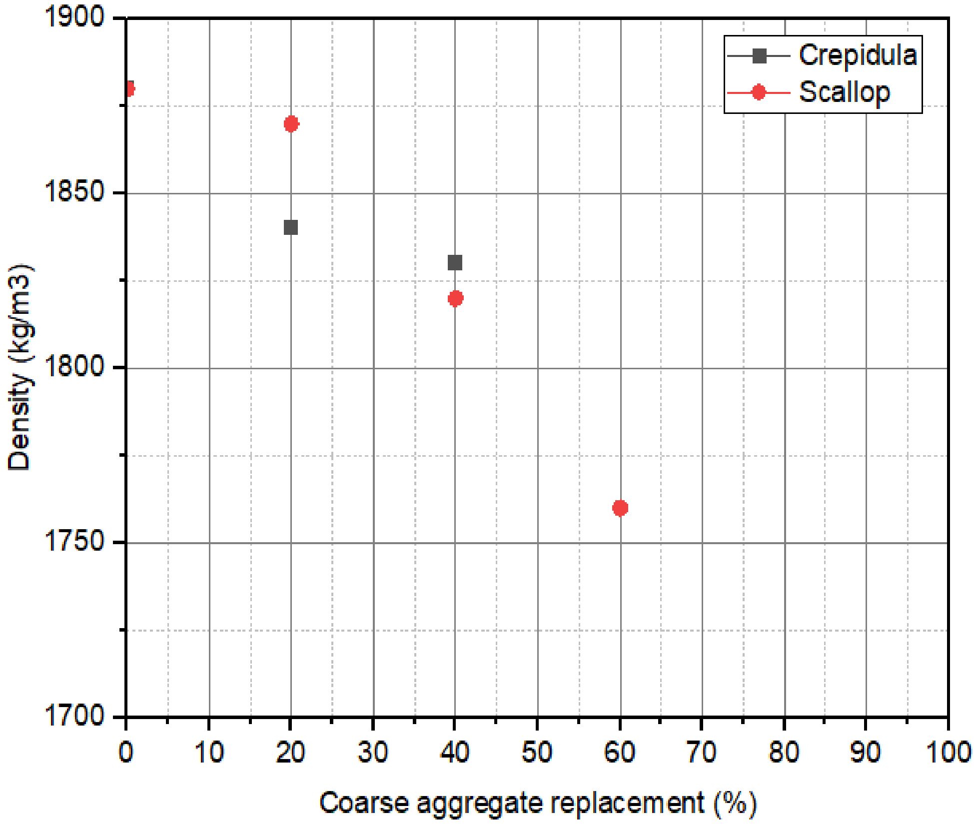

Figure 4. The fresh density of seashell-based pervious concrete

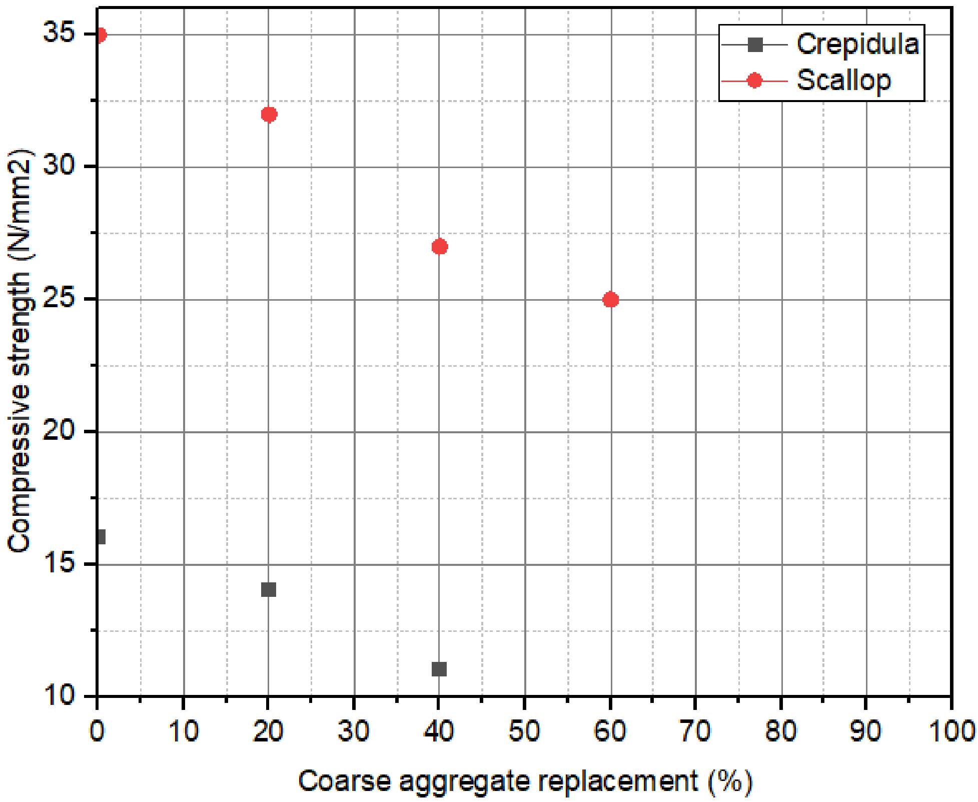

Figure 5. 28-day compressive strength of seashell-based pervious concrete

4. Conclusions

This review article examined the properties of seashells and discussed their applications in the sector. Based on the above discussion, it is concluded that:

- Seashell aggregates used in cemented materials should be generally cleaned to eliminate salts and organic matter.
- Seashell aggregate physical properties are affected by the aggregate size and affect most cemented material properties.
- Seashell loss on ignition varies between 41 and 51% and the content of calcium oxide is between 35 and 54%.
- The natural fine aggregate can be substituted for crushed seashells by up to 25% by weight to produce standard ordinary concrete with adequate strength and density.
- The authors who intended to use the shells as an additive to the cement found no disturbance in the hydration of the cement.
- The production of pervious concrete from seashells is possible, provided that an appropriate compaction method is applied.

Finally, according to all the studies carried out on the valorization of shells in a cemented material, from the viewpoint of the facility of use, mechanical performance, and durability, the shells seem to be an interesting candidate for incorporation in ordinary concrete and pervious concrete.

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