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Utilization of ground waste seashells in cement mortars for masonry and plastering

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ABSTRACT

In this research, four types of waste seashells, including short-necked clam, green mussel, oyster, and cockle, were investigated experimentally to develop a cement product for masonry and plastering. The parameters studied included water demand, setting time, compressive strength, drying shrinkage and thermal conductivity of the mortars. These properties were compared with those of a control mortar that was made of a conventional Portland cement. The main parameter of this study was the proportion of ground seashells used as cement replacement (5%, 10%, 15%, or 20% by weight). Incorporation of ground seashells resulted in reduced water demand and extended setting times of the mortars, which are advantages for rendering and plastering in hot climates. All mortars containing ground seashells yielded adequate strength, less shrinkage with drying and lower thermal conductivity compared to the conventional cement. The results indicate that ground seashells can be applied as a cement replacement in mortar mixes and may improve the workability of rendering and plastering mortar.

1. Introduction

Each year, more than 15 million tons of municipal solid waste is collected in Thailand. This total amount has increased steadily during the last decade (Chiemchaisri et al., 2007; Pollution Control Department, 2010). Bones and seashells comprise approximately 0.9% of the total waste. Although most of these wastes currently are incinerated or land-filled (Chaiya and Gheewala, 2007), environmental concerns demand the development of an effective waste utilization process.

The chemical composition of shells is >90% calcium carbonate ($CaCO_3$) by weight (Falade, 1995; Yoon et al., 2003, 2004; Yang et al., 2005; Ballester et al., 2007; Mosher et al., 2010); this composition is similar to limestone powder or dust-like stone powder from grinding limestone to produce Portland cement. Ground seashells also are used as an ingredient of cement or sand replacements in concrete production to save costs. Interestingly, the crystal structures of green mussel and cockle shells are largely composed of aragonite and calcite, which have higher strengths and densities than limestone powder (Mosher et al., 2010).

The use of ground seashells as a stone-like substitute material to produce concrete and mortar has been studied previously. For example, a freshwater snail, genus *Viviparus*, has been utilized as an alternative aggregate in concrete. When the replacement level of freshwater snail in the concrete mix is increased, the compressive and tensile strengths and workability of the concrete decrease (Falade, 1995). A study of ground oyster shells found that the shell is mainly composed of calcium carbonate and small organic compounds (Yoon et al., 2003, 2004). The calcium carbonate crystallizes in the form of calcite, which has particles that are rounder and lighter than those of sand. The use of ground oyster shells to replace sand does not significantly decrease the compressive strength of the mortar (Yoon et al., 2003, 2004). Ground oyster shell also does not react with Portland cement, and the workability of concrete is decreased when the fineness modulus decreases. The higher the replacement levels of ground shell oyster in sand, the higher the rate of the development of compressive strength, and the lower the elasticity modulus (Yang et al., 2005). Ground particles of mussel shell reportedly have slender needle-like shapes, unlike limestone that has a round shape. As a result, the internal morphology of mortar mixed with mussel shells has a structured mesh and smaller pores. Thus, the inclusion of mussel shells in mortar results in higher compressive and bending strengths than that of mortar mixed with limestone powder (Ballester et al., 2007).

Various powder materials strongly affect the shrinkage of mortar. For instance, some types of fly ash enhance expansion in

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mortar and can compensate slightly for shrinkage. The use of silica fume can reduce drying shrinkage due to the increased density of concrete. Limestone powder can be used to improve the properties of masonry and plastering cement. Mixing limestone powder in mortar decreases the drying shrinkage, because limestone powder is relatively inert and is classified as a kind of aggregate (Manjit and Mridul, 2002; Mun et al., 2007; Benachour et al., 2008).

Short-necked clam, green mussel, oyster, and cockle are the most popular shellfish consumed in Thailand (Department of Fisheries, 2006). The aim of this research was to study the use of these 4 types of waste seashells as replacement materials in the production of plastering cement suitable for general application.

2. Experimental program

2.1. Materials

ASTM Type 1 Portland cement was used in this study. Graded fine river sand, with a fineness modulus of 1.88, specific gravity of 2.64, and water absorption of 1.30%, was used as a fine aggregate. The fine aggregate used was finer than the recommendations of the ASTM C33 standards, which stipulate that the fineness modulus should be within 2.30–3.10. The particle size distribution of fine sand obtained from sieve analysis was within the range required by the TIS 1776 and BS 882 standards (Figs. 1 and 2, respectively).

Four types of seashells, from Samut Songkhram province (green mussel shell), Surat Thani province (short-necked clam and cockle shells), and Chanthaburi province (oyster shell), were used. The seashells were cleaned, dried, and then ground by a coarse grinding machine, with electrical energy consumption of 0.5–0.7 kWh/kg of ground seashell. The ground shells were passed through a sieve No. 4 (4.47 mm). The seashell was then wet-milled with water into a ball mill grinder rotating with steel balls inside for 3–4 h to further pulverize the seashell until the particle sizes were smaller than a sieve No. 200 (0.075 mm). Approximately 0.4–0.7 L of water and 2.5–3.2 kWh of energy per kilogram of ground seashell were required for this process. Finally, the ground shells were dried in a drying oven at a temperature of 110 ± 5 °C for 24 h, with energy consumption of 0.1–0.3 kWh/kg of ground seashell.

2.2. Mortar mix proportion

Mortars were mixed with a cement-to-sand ratio of 1:4. The water-to-cement ratio conformed to a specified flow rate of 110% ± 5%. Portland cement Type 1 was partially replaced with 5%, 10%, 15%, or 20% ground seashells by weight of binder. The mixture proportions of the mortars studied are summarized in Table 1. OPC denotes the control mortar mixed with Portland cement Type 1. SCS(*X*), GMS(*X*), OS(*X*), and CS(*X*) denote mortars in which ground short-necked clam shell, green mussel shell, oyster shell, and cockle shell, respectively, were used as Portland cement replacements at *X* % by weight.

2.3. Testing procedures

1. The chemical compositions of the ground seashells were determined by use of X-ray fluorescence spectrometry. Chloride and sulfate contents were determined by titration and sedimentation methods.
2. The physical properties of the ground seashells tested included the following: specific gravity (compliance with ASTM C188); Blaine fineness (compliance with ASTM C204); strength index (compliance with ASTM C311); particle morphology, as examined through a scanning electron microscope (SEM); and particle size distribution, as examined through a laser particle size analyzer.
3. The physical properties of the aggregate materials tested included the following: specific gravity and water absorption of fine sand (according to ASTM C128); and particle size and fineness modulus of fine sand (according to TIS 1776 and BS 882) (Thai Industrial Standards Institute, 1999; British Standard Institution, 1992).
4. The properties of cement mortars tested included the following: flow value for conformity to proper water content (according to ASTM C109); initial and final setting times (according to ASTM C807); compressive strengths of mortar at 3, 7, 14, 28, and 60 days (according to ASTM C109); and drying shrinkage (according to ASTM C596). Three mortar specimens were tested for each data.
5. The thermal conductivity of cement mortars were tested according to JIS R2618 (Japanese Standards Association, 1992). The measurement equipment consisted of two electrical circuits, namely a power supply and a temperature measurement. A 0.3 mm dia. Platinum wire (hot wire), with a thermocouple or temperature measurement welded onto it, was placed between the center of the faces of two straight specimens tightly fastened to each other at two positions near the ends. Then the specimen was placed inside the furnace and was heated to prescribed temperatures. Predefined different currents were passed through the hot wire. By continuously

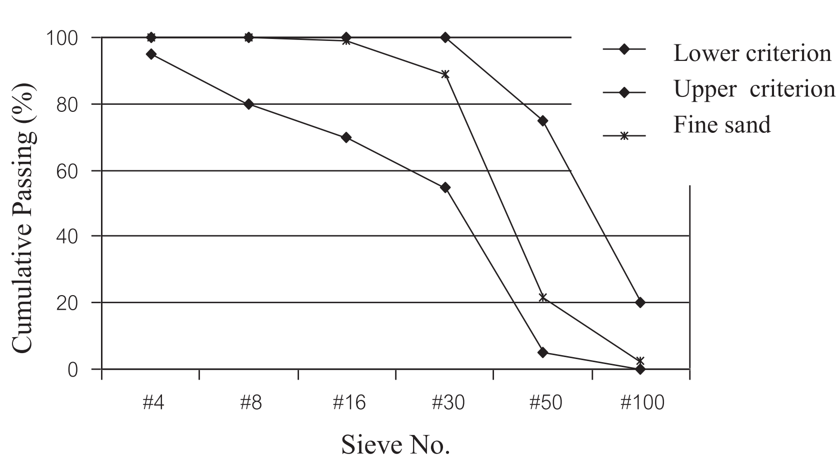

Fig. 1. Particle size distribution of fine aggregate compared to TIS 1776 standard.

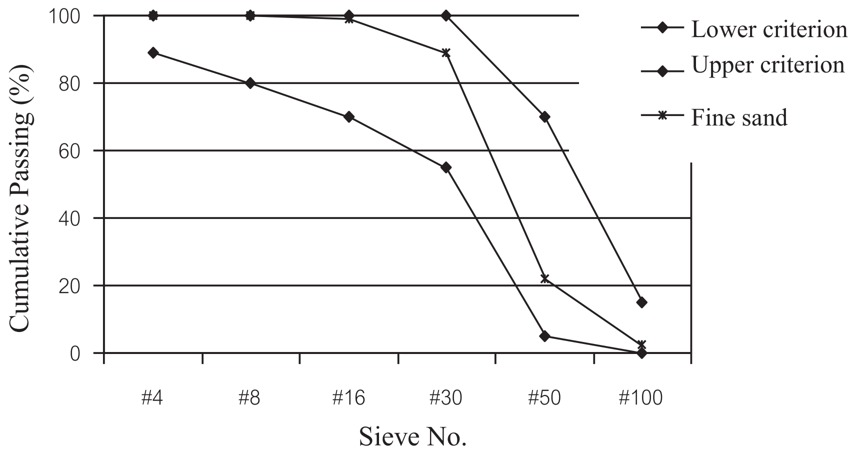

Fig. 2. Particle size distribution of fine aggregate compared to BS 882 standard.

maintaining a uniform temperature and applying different currents to the hot wire, the increase in temperature of the hot wire was measured three times at each current level, and the value of the thermal conductivity was calculated. Three mortar specimens were tested for each data.

3. Test results and discussion

3.1. Properties of ground seashells

The chemical compositions of cement and ground seashells are given in Table 2. Calcium carbonate was the main component of the short-necked clam, green mussel, oyster, and cockle shells, at 96.80%, 95.60%, 96.87%, and 97.13%, respectively. The hydrochloric acid and chloride (Cl) contents ranged 0.01%–0.02%, and the sulfate content (SO_4) ranged 0.06%–0.43%. The presence of chloride and sulfate was due to the passage of the materials through a wetting process, in which hydrochloric acid was dissolved partially in water.

The physical properties of the different ground seashells are shown in Table 3. The weight loss due to ignition (LOI) of the ground seashells was large, ranging 42%–43%, because calcium carbonate undergoes thermal decomposition into calcium oxide and carbon dioxide at controlled burning temperatures of >550 °C. The Blain-specific surface areas of ground short-necked clam, green mussel, oyster, and cockle shells were 8279, 6186, 14,280 and 8299 cm^2/g, respectively. The Blain fineness of the ground oyster was finer than those of the other seashells, implying better strength development due to improvement of the pozzolanic reaction (Chindaprasirt and Rukzon, 2008).

The SEM micrographs and particle size distributions are shown in Figs. 3 and 4. The morphologies of the 4 types of ground seashells showed irregularly shaped particles, multiangle shapes, and some slender particles. There were also larger mixed surface areas, quite rough but relatively smooth and with low porosity. The average size of the particles of Portland cement and the short-necked clam, green mussel, oyster, and cockle shells were 22.82, 20.80, 29.87, 13.93, and 13.56 μm, respectively. It was found that 80% by volume of the ground cockle and oyster shell particles were distributed in the range of 0.5–20 μm, and the ground short-necked clam and green mussel shells were distributed in the range of 0.5–40 μm.

3.2. Properties of mortar containing ground seashells

3.2.1. Water requirement and setting time of mortar

When the proportion of ground shells replacing Portland cement increased, there was an increase in the flow value of the cement mortar. The replacement of cement with ground seashells decreased the amount of cementitious material and increased the free water content in the mix. This process was increasingly seen as the percentage replacement of seashells was increased. In addition, some particles were somewhat flat and of low porosity, which

Table 1
Mix proportions of mortar.

Mix	Portland cement (g)	Ground seashells (g)	Sand (g)	Water (g)	Ratio by weight of cement:sand:ground seashell
OPC	374	0	1497	387	1:4:0
SCS (5)	356	19	1497	371	0.95:4:0.05
SCS (10)	337	37	1497	365	0.90:4:0.10
SCS (15)	318	56	1497	356	0.85:4:0.15
SCS (20)	299	75	1497	337	0.80:4:0.20
GMS (5)	356	19	1497	356	0.95:4:0.05
GMS (10)	337	37	1497	341	0.90:4:0.10
GMS (15)	318	56	1497	318	0.85:4:0.15
GMS (20)	299	75	1497	301	0.80:4:0.20
OS (5)	356	19	1497	372	0.95:4:0.05
OS (10)	337	37	1497	369	0.90:4:0.10
OS (15)	318	56	1497	365	0.85:4:0.15
OS (20)	299	75	1497	352	0.80:4:0.20
CS (5)	356	19	1497	374	0.95:4:0.05
CS (10)	337	37	1497	365	0.90:4:0.10
CS (15)	318	56	1497	357	0.85:4:0.15
CS (20)	299	75	1497	350	0.80:4:0.20

Table 2
Chemical compositions of cement and ground seashells.

Chemical compositions (%)	Materials				
	Portland cement	SCS	GMS	OS	CS
SiO_2	20.3	0.84	0.73	1.01	0.98
Al_2O_3	5.18	0.14	0.13	0.14	0.17
Fe_2O_3	3.21	0.06	0.05	0.07	0.06
CaO	65.15	53.99	53.38	53.59	54.24
MgO	1.17	0.08	0.03	0.46	0.02
K_2O	0.29	0.03	0.02	0.02	0.03
Na_2O	0.04	0.39	0.44	0.23	0.37
SO_3	2.82	0.16	0.34	0.75	0.13
Cl	0.008	0.02	0.02	0.01	0.01
SO_4	3.76	0.06	0.11	0.43	0.07
Free CaO	1.25	–	–	–	–
$CaCO_3$	–	96.8	95.6	96.8	97.13

Table 3
Physical properties of Portland cement (PC) and ground seashells.

Physical properties	Materials				
	PC	SCS	GMS	OS	CS
Loss in ignition (LOI) (%)	1.83	42.73	42.22	42.83	42.87
Moisture content (%)	0.08	0.26	0.47	0.36	0.15
Specific gravity	3.11	2.71	2.86	2.65	2.82
Water requirement (%)	100	100	101	101	99
Blain-specific surface area (cm^2/g)	3376	8279	6186	14,280	8299
Fineness (Accumulated passing) (%)					
$\geq$ 75 μm	3.28	4.73	10.62	2.89	1.90
75 μm	9.88	7.44	7.38	3.89	4.22
45 μm	10.02	7.31	6.54	4.22	4.87
$\leq$ 36 μm	76.78	80.52	75.46	89.01	89.02
Strength index (%)					
at 7 days	100	31.16	66.38	86.34	63.68
at 28 days	100	25.08	59.14	73.82	58.83

decreased the water retention in the mortar. Thus, increasing the replacement ratio of ground seashells reduced the water retainability in the pores of the particles. This scenario altered the friction between the ground seashells and Portland cement particles, and resulted in a lower water requirement than that required in the TIS 1776 and ASTM C109 standards (which state that the flow value should be 110% ± 5%).

The water requirement of ground oyster shell was much higher than those of the other ground seashells. Owing to its relatively high specific surface area, more water was required to coat the ground oyster shell particles than was needed for the other seashell types. Ground green mussel shell had the lowest specific surface area and largest particle size; accordingly, the surface area to react with Portland cement was less than that for the other seashells. Consequently, ground green mussel had the lowest water requirement (Fig. 5).

When the ratio of replacement of ground seashells in Portland cement increased, there was an increase in the initial setting times of formation. The high volume replacement with ground seashell disturbs the hydration reaction, due to a decreasing content of Portland cement in the mortar mix. In other words, mortar containing ground seashell has a longer initial setting time than the control mortar. The TIS 1776 standards indicate that the setting time of mortar should be ≥60 min; mortars mixed with ground seashells corresponded to the standard requirements. When the replacement ratios of the ground seashells were increased, the final setting times of the seashell-containing mortars were higher than those of the control mortars (Fig. 6).

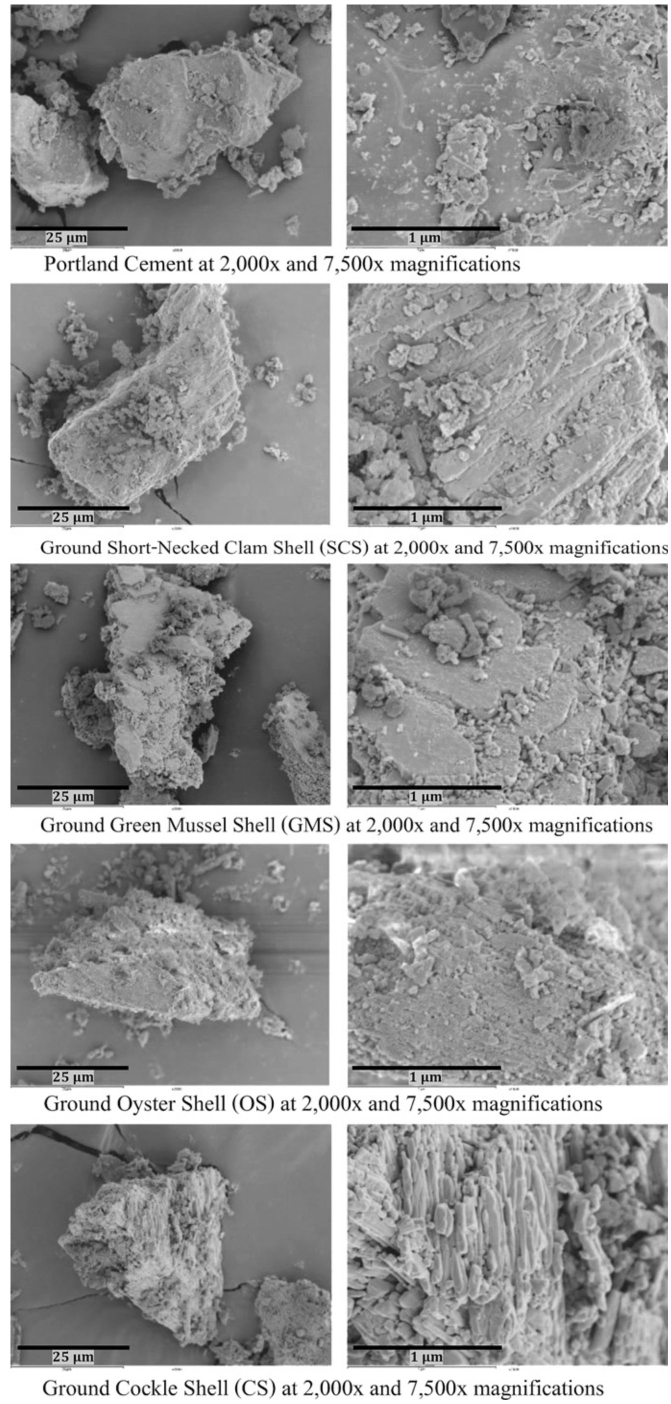

Fig. 3. Micrographs of Portland cement and ground seashells.

3.2.2. *Compressive strength of mortar*

Increasing the percentage replacement of ground short-necked clam, oyster, and cockle seashells tended to reduce the compressive strength of the mortars, because the less reactive material of ground seashell mixed with the Portland cement. However, because the particle sizes of the 3 types of ground seashells were a little smaller than those of Portland cement, the small particles of ground seashells acted as a filler material, inserting themselves into the void of the Portland cement. Therefore, the compressive strengths of the seashell-containing mortars were a little lower than that of the control mortar.

The compressive strengths of seashell-containing mortars consistently increased with increased curing time (Figs. 7–9). The compressive strengths of mortars mixed with green mussel decreased with higher Portland cement replacement. Moreover, the particle size of ground green mussel was somewhat larger than that of the Portland cement, resulting in a lower particle packing density. Thus, the compressive strength was considerably lower than that of the control mortar (Fig. 10). The compressive strengths of the mortars mixed with ground seashells at 28 days were adequate and higher than the value required by TIS 1776 and ASTM C270 (Fig. 11). However, unlike the workability and plasticity, the compressive strength is not of prime importance for rendering and plastering applications (Malhotra and Dave, 1999).

3.2.3. *Drying shrinkage of mortar*

Figs. 12–15 show the drying shrinkages of mortars mixed with ground seashells. One source of drying shrinkage in mortar is the

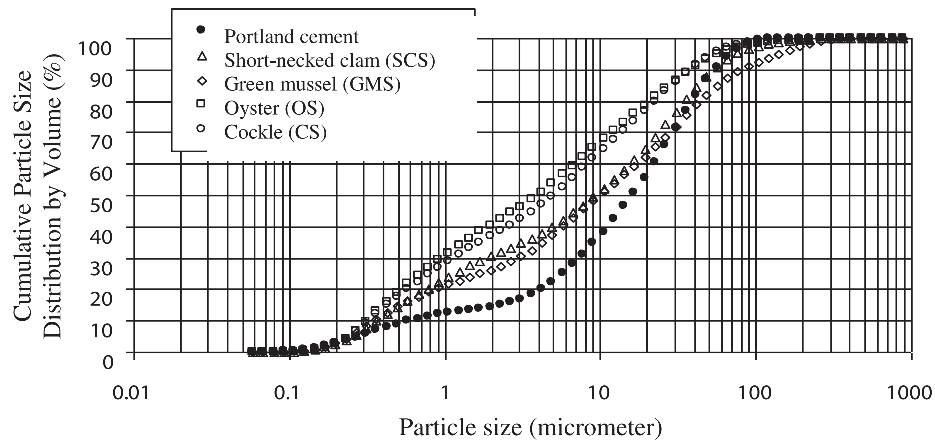

Fig. 4. The cumulative particles size distribution of cement and ground seashell particles.

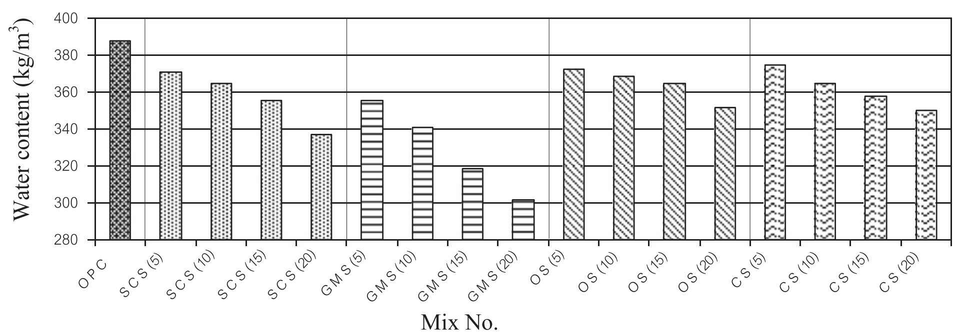

Fig. 5. Water requirements of mortars containing ground seashells.

loss of the water held in the capillary pores of the hydrated cement paste to the environment (de Sensale, 2006).

The drying shrinkages of mortars containing ground short-necked clam and ground oyster shells were similar, due to the small quantities of ground short-necked clam and ground oyster shells in Portland cement not affecting the pore structure of the mortar. Compared with the control mortar, the mortars mixed with these ground seashells had lower shrinkages than the control. A higher volume of ground oyster and short-necked clam shells can cause low shrinkage, owing to the greater fineness of these ground seashells compared to cement. Therefore, the ground shell particles can insert themselves in the void between the cement particles (Chatveera and Lertwattanaruk, 2011). The incorporation of these ground seashells causes the segmentation of large pores, leading to refinement of the pore structure. It also increases the number of nucleation sites for the precipitation of pozzolanic reaction products in cement paste (Rukzon et al., 2009). This process causes a denser internal structure, decreased internal void, and decreased shrinkage.

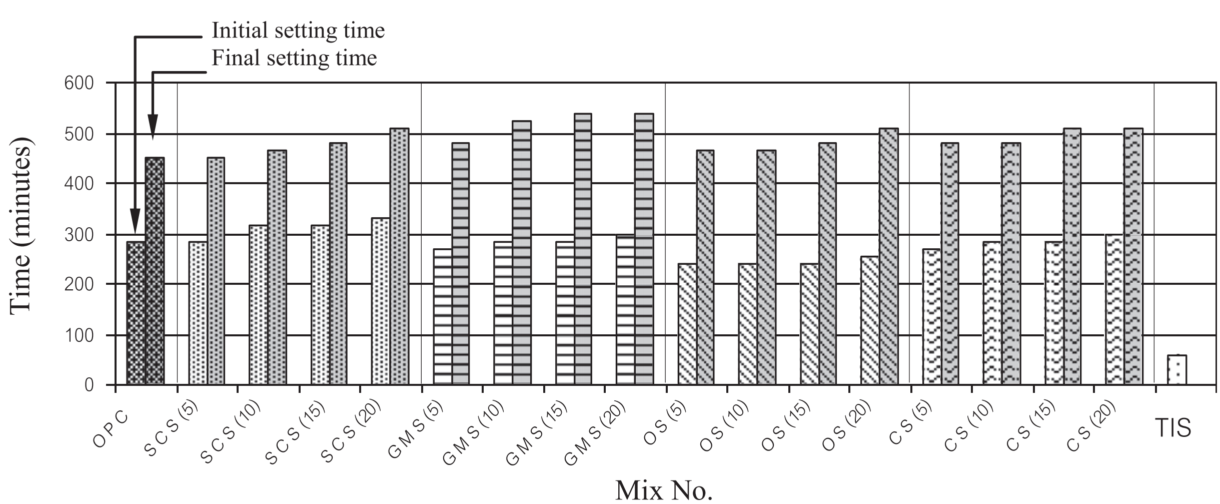

Fig. 6. Setting times of mortars containing ground seashells.

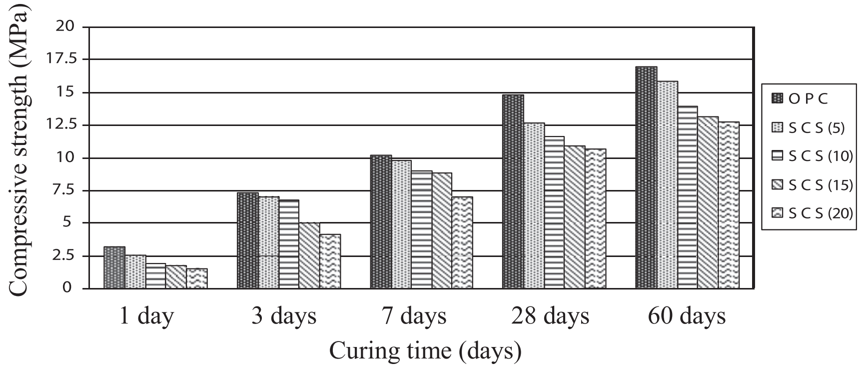

Fig. 7. Compressive strengths of mortars containing ground short-necked clam shell (SCS).

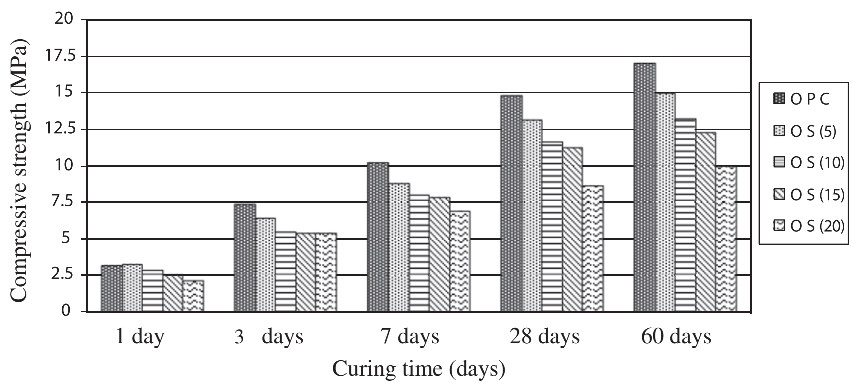

Fig. 8. Compressive strengths of mortars containing ground oyster shell (OS).

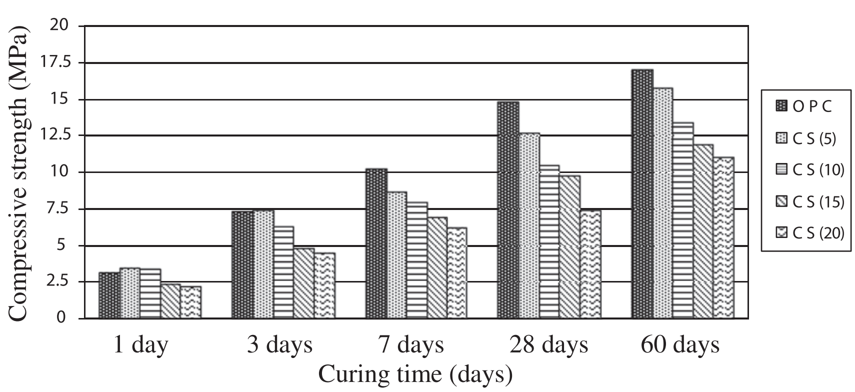

Fig. 9. Compressive strengths of mortars containing ground cockle shell (CS).

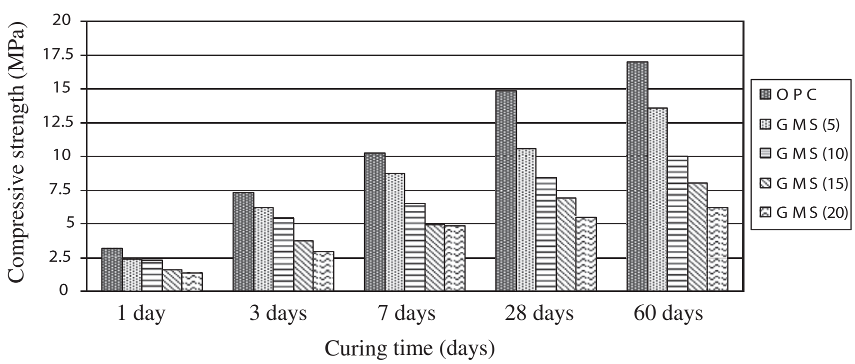

Fig. 10. Compressive strengths of mortars containing ground green mussel shell (GMS).

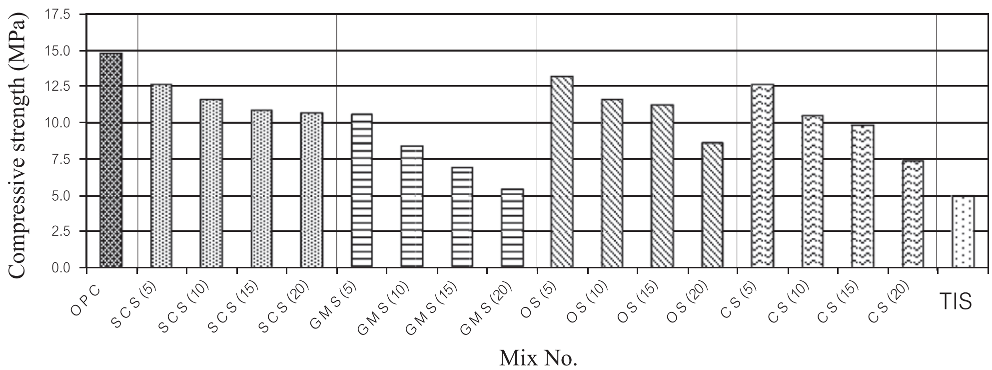

Fig. 11. Compressive strengths at 28 days of mortars containing ground seashells.

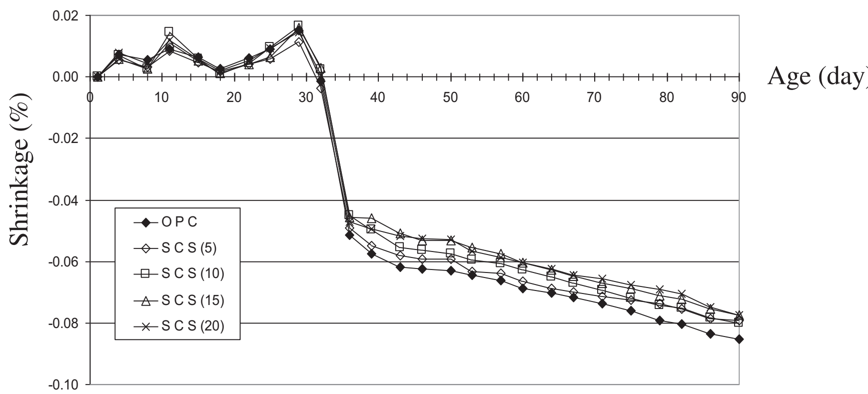

Fig. 12. Drying shrinkage of mortar mixed with ground short-necked clam (SCS).

The drying shrinkage of the ground short-necked clam-mixed mortar was lower than that of the mortar mixed with ground oyster.

The drying shrinkages of the mortars mixed with ground green mussel and ground cockle were similar, due to small quantities of green mussel and cockle in the Portland cement not affecting the pore structure of the mortar. Compared with the control mortar, the mortars mixed with these ground seashells had higher shrinkages than the control. The higher volume of the ground green mussel shells can cause increased shrinkage of mortar, because its fineness is lower than that of the Portland cement. Therefore, the particles cannot insert themselves in the void between the cement particles. This situation leads to a less-dense internal structure, increased internal void, and increased shrinkage. The drying shrinkage of the ground green mussel-containing mortar was higher than that of the mortar mixed with ground cockle. The mortars containing ground short-necked clam with the average particle size of 20.80 μm yield minimal long-term shrinkage when compared to the other mortars.

3.2.4. Thermal conductivity of mortar

The results in Fig. 16 show that the highest thermal conductivity of the control mortar is 1.56 W/m-K. Compared with the control

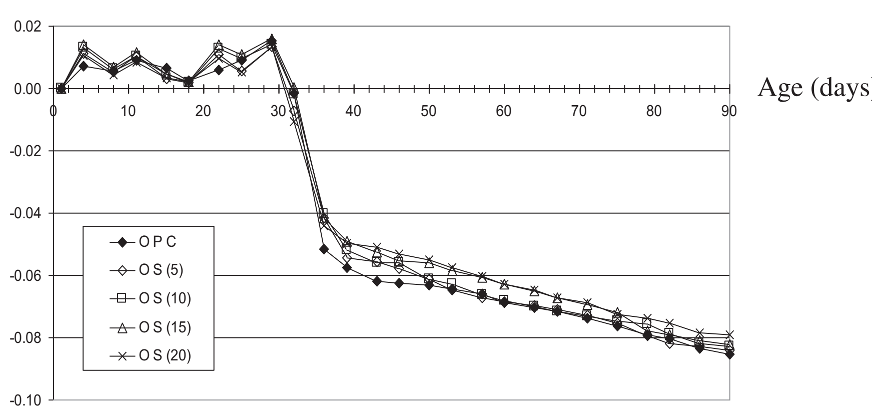

Fig. 13. Drying shrinkage of mortar mixed with ground oyster (OS).

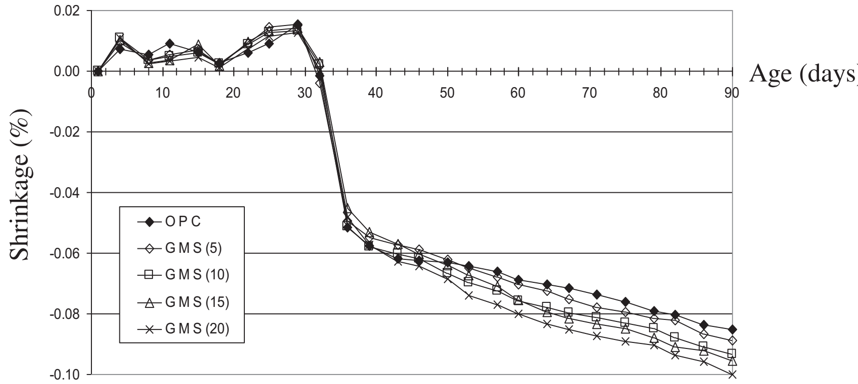

Fig. 14. Drying shrinkage of mortar mixed with ground green mussel (GMS).

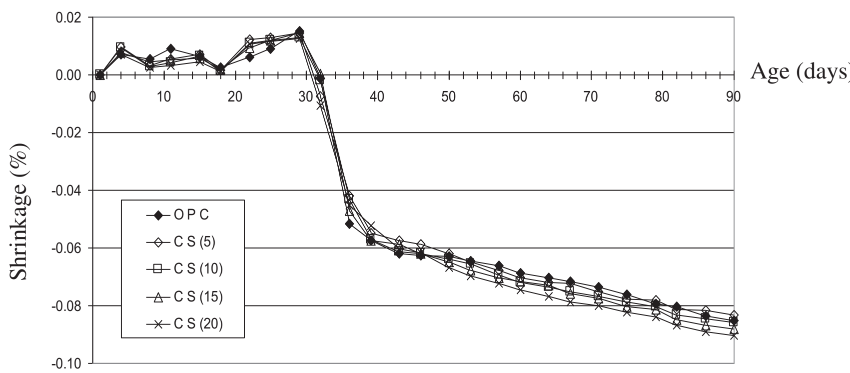

Fig. 15. Drying shrinkage of mortar mixed with ground cockle (CS).

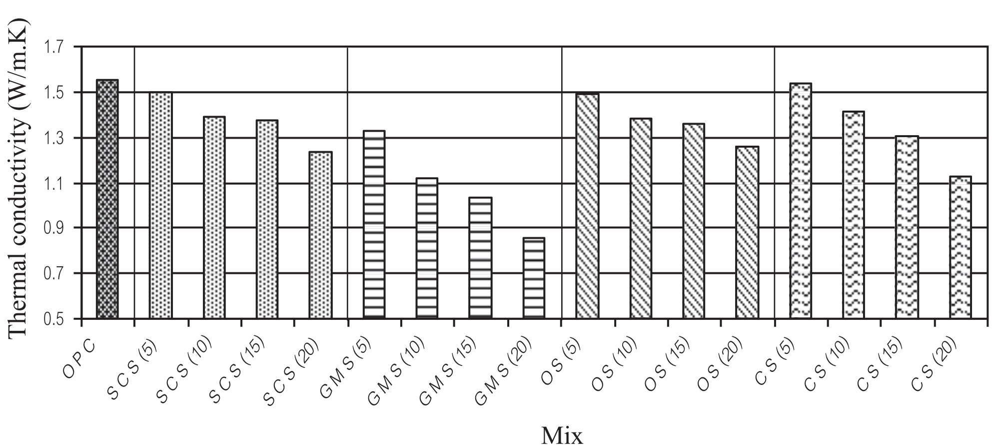

Fig. 16. Thermal conductivities of mortars mixed with ground seashells.

mortar, the mortars mixed with 4 types of ground seashells had lower thermal conductivity than the control. Increasing the percentage replacement of ground seashells tended to reduce the thermal conductivity of the mortars, due to the lower specific gravity of these ground seashells compared to the cement. The incorporation of these ground seashells caused a lower density of mortar, leading to an increase in porosity and lowering the thermal conductivity. However, the mortars containing ground green mussel shows the lowest thermal conductivity especially at the percentage replacement of 20% by weight of binder because ground green mussel shell had the largest particle size and lowest specific surface area to cause an increase in the size of capillary pores. This situation leads to a less-dense internal structure and lowering the thermal conductivity. Materials with lower thermal conductivity provide better thermal insulation.

4. Conclusions

Four types of ground seashells were incorporated into normal Portland cement. Comparable properties of the seashell-containing mortars for plastering and masonry construction were obtained with each of the 4 seashell types. The following conclusions can be drawn:

1) By using a wet ball mill for grinding seashells to relatively fine particles comparable to Portland cement, the average sizes of ground short-necked clam, green mussel, oyster, and cockle were 20.80, 29.87, 13.93, and 13.56 μm, respectively as compared to 22.82 μm of Portland cement particles. The main chemical composition of ground seashells was calcium carbonate, in the range of 96%–97%. The Blain fineness of the ground oyster shell was finer than those of other seashells, implying better strength development.
2) Increasing the percentage replacement of ground seashells in Portland cement improved the water requirement and the setting times of the mortars. The incorporation of ground seashells reduced the water demand of mortar and improved the workability. The setting times of ground seashell mortars were extended. These are important advantages for masonry construction and plastering in hot climates.
3) The compressive strengths of mortars containing ground seashells were decreased compared with the control mortar. Replacement with ground green mussel in Portland cement led to lower compressive strengths than those obtained with the other 3 types of ground seashells. However, the compressive strengths of ground seashell mortars were adequate and higher than those required by standards for plastering.
4) Replacement with ground short-necked clam and ground oyster in Portland cement led to decreased drying shrinkages of mortars compared with the control mortar. Mortar mixed with ground short-necked clam had a lower shrinkage than the ground oyster-mixed mortar. Replacement with ground green mussel and ground cockle led to increased drying shrinkages of the mortars compared with the control mortar.
5) The thermal conductivities of mortars containing ground seashells were decreased compared with the control mortar. Replacement of ground green mussel in Portland cement led to lower thermal conductivities than those obtained with the other 3 types of ground seashells. When increasing the replacement percentage of ground seashells (from 5% to 20% by weight of binder), the thermal conductivity of mortar decreases by 1%–45% compared with that of the OPC mortar. It can be used in building construction to provide better thermal insulation.
6) For overall performance, the mortars containing high volume of ground short-necked clam yield the optimum properties compared to the other ground seashells such as a relatively low mixing water requirement, increased setting time, good compressive strength, lower drying shrinkage, and decrease in thermal conductivity.

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