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Rock wool wastes as a supplementary cementitious material replacement in cement-based composites

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Abstract. The use of rock wool waste, an industrial by-product, in cement-based composites has positive effects on the environment because it reduces the problems associated rock wool disposal. The experiments in this study tested cement-based composites using various rock wool waste contents (10, 20, 30 and 40% by weight of cement) as a partial replacement for Portland cement in mortars. The pozzolanic strength activity test, flow test, compressive strength test, dry shrinkage test, absorption test, initial surface absorption test and scanning electron microscope observations were conducted to evaluate the properties of cement-based composites. Test results demonstrate that the pozzolanic strength activity index for rock wool waste specimens is 103% after 91 days. The inclusion of rock wool waste in cement-based composites decreases its dry shrinkage and initial surface absorption, and increases its compressive strength. These improved properties are the result of the dense structure achieved by the filling effect and pozzolanic reactions of the rock wool waste. The addition of 30% and 10% rock wool wastes to cement is the optimal amount based on the results of compressive strength and initial surface absorption for a w/cm of 0.35 and 0.55, respectively. Therefore, it is feasible to utilize rock wool waste as a partial replacement of cement in cement-based composites.

Keywords: rock wool waste; pozzolanic strength activity index; initial surface absorption test; waste treatment

1. Introduction

Rock wool is an inorganic fibrous substance produced by steam blasting and cooling molten glass. Rock wool is frequently used in acoustic insulation, fire protection, cement reinforcement, pipe insulation, and even as synthetic soil for growing plants (Milena and Robert 2006). Taiwan Environmental Protection Administration (2010) generates more than 100 million tons of rock wool waste annually. The amount of rock wool insulation material waste in nuclear power plants has reached high levels over the last few decades. Fuel cycle and materials administration in Taiwan (2011) indicates that the amount of stored rock wool waste has increased dramatically in

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the past decade. Reducing the quantity of the rock wool waste in storage is an important issue.

Rock wool waste is loose and bulky, and occupies a large space when stockpiled or landfilled. Traditional landfill or stockpile methods are not environment-friendly disposal methods, and have great difficulty meeting Environmental Protection Agency regulations (Wei and Huang 2001, Chen *et al.* 2006). Alternative treatment methods include melting, compressing, briquetting, and reprocessing (Wang 2003, Premur and Salopek 2004). However, the melting process requires a lot of energy to heat the waste, and has proven to be uneconomical. In recent years, the supplementary cementitious materials (SCMs) have often been used to replace a portion of the aggregates or cementitious materials in cement-based composites, with the aim of improving mechanical properties or durability (Ramachandran *et al.* 2001). SCMs are divided into two main classifications: natural pozzolans and industry by-product materials. Like other industry by-product materials, such as fly ash, silica fume and ground granulated blastfurnace slag (GGBS), rock wool waste can be reused and recycled to alleviate the environmental problems created by civil construction (ACI 232.1R 2000, ACI 233R 2001, ACI 202.2R 2004, Cheng *et al.* 2005, ACI 234R 2006, Lin *et al.* 2008, Lin *et al.* 2009). The application of these materials depends on the chemical composition and grain size of the by-product. Cheng showed that the composition of rock wool waste is similar to other pozzolanic materials, and that rock wool waste is a suitable substitute for coarse and fine aggregates (Cheng *et al.* 2011). The use of rock wool wastes also enhances the mechanical properties and durability of concrete. These findings suggest that rock wool waste may be a SCM.

This study evaluates the effects of rock wool waste on the properties of cement-based composites. The rock wool waste served as a partial replacement of cement in various mixtures. The pozzolanic strength activity index (PSAI) test, flow test, compressive strength test, dry shrinkage test, absorption test, initial surface absorption test (ISAT) and scanning electron microscope (SEM) observations were conducted to evaluate the properties of cement-based composites. This study also reports the influence of different percentages of rock wool waste as partial replacements of cement in the mortar.


(a) Before crushed and ground


(b) Compressor


(c) After crushed and ground


(d) Appearance of rock wool wastes

Fig. 1 Crushed and ground procedures of rock wool wastes

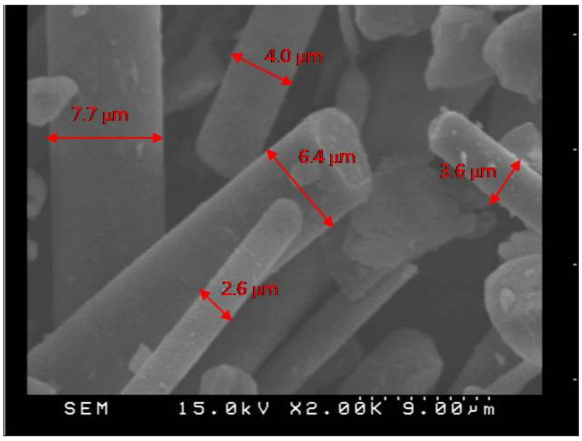


Fig. 2 SEM observation of rock wool wastes (x2000)

Table 1 Chemical composition of various recycled materials and Portland cement

Chemical composition	Rock wool	Fly ash	GGBS	Silica fume	Portland cement
SiO_2 (wt.%)	38.7	54.0	33.5	91.5	21.2
Al_2O_3 (wt.%)	18.6	24.0	9.0	0.2	5.4
Fe_2O_3 (wt.%)	5.3	8.0	3.6	0.7	3.2
CaO (wt.%)	20.9	2.0	43.8	0.4	63.8
MgO (wt.%)	7.0	1.3	2.7	1.5	2.0
K_2O+Na_2O (wt.%)	2.0	0.9	0.6	1.9	0.8
Other (wt.%)	7.5	9.8	6.8	3.8	3.6
Surface area (m^2/kg)	206	420	415	22500	364

2. Experimental program

2.1 Materials

Rock wool waste obtained from thermal insulation materials was crushed and ground (Fig. 1). Table 1 lists the chemical composition of rock wool wastes and various recycled materials. The amount of SiO_2 in rock wool wastes is 38.7%, which has higher SiO_2 content than GGBS. The specific gravity and absorption of the rock wool wastes is 2.80 and 2.50%, respectively. The grain sizes of rock wool wastes passing through sieve #200 (75 μm) were used in this study. The scanning electron microscope (SEM) image in Fig. 2 shows that rock wool waste particles have a cylindrical shape, with a range of the diameter from 2.6 μm to 7.7 μm. In addition, the surface area of rock wool waste particles is approximately 206 m^2/kg, which is lower than that of other recycled materials and cement.

2.2 Mix proportion

Type I Portland cement conforming to ASTM C150-09 was used in all mixes. Table 2 shows the mix properties of mortar specimens. The water/cement ratios (*w*/cm) were 0.35 and 0.55 and

Table 2 Mix proportions (kg/m^3)

Mix no.	w/cm*	Rock wool content (wt. %)	Water	Cement	Rock wool	Fine aggregate	SP**
A	0.35	0 %	191.8	564.1	0.0	1551.2	5.0
AR10		10 %	191.6	507.7	56.4	1549.7	5.0
AR20		20 %	191.4	451.3	112.8	1548.1	5.0
AR30		30 %	191.2	394.9	169.2	1546.6	5.0
AR40		40 %	191.0	338.5	225.6	1545.0	5.0
B	0.55	0 %	278.8	506.9	0.0	1394.0	0.0
BR10		10 %	278.5	456.2	50.7	1392.7	0.0
BR20		20 %	278.3	405.5	101.4	1391.5	0.0
BR30		30 %	278.0	354.8	152.1	1390.2	0.0
BR40		40 %	277.8	304.1	202.8	1388.9	0.0

* water/cementitious ratio
** superplasticizer

the sand/binder ratios were kept at a constant of 2.75. Rock wool waste (10%, 20%, 30% and 40% by weight) was added to different mixes to partially replace the cement. The fine aggregates had a fineness modulus of 2.51. The absorption of fine aggregates was 0.63%, with a relative density of 2.49 under the saturated surface dry (SSD) condition. Proper mixture was achieved using a high-range water-reducing admixture (superplasticizer). The rock wool waste had a particle size of less than 75 μm.

2.3 Specimens

The experiments in this study cast a total of 200 specimens made of 10 different mixes. All specimens were cured in saturated limewater until testing. For each mix, 50 x 50 x 50 mm cube specimens were prepared to test the PSAI, compressive strength, and absorption, while ψ100 x 50 mm circular specimens were used for the ISAT. Finally, specimens measuring 285 x 25 x 25 mm were prepared for the dry shrinkage test and the specimens of 10 x 10 x 10 mm were prepared for the SEM observation.

2.4 Testing methods

In accordance with ASTM C109-11, compressive strength tests were performed at 7, 28 and 91 days. Absorption was measured following the specifications of ASTM C642-06 after 91 days. The drying shrinkage and SEM observation was carried out following the ASTM C596-09 and ASTM C856-11 after 91 days, respectively.

Flow was determined by ASTM C1437-07. A cone-shaped mold was filled with fresh mix in two lifts and placed at the center of a flow table. When the mold was removed, the vibrating table was dropped 25 times in 15 seconds. The diameter (mm) of the specimens was measured along four lines.

The ISAT was performed in accordance with BS 1881-208 measured the absorptive characteristics of the surface. When the specimens cured up to 91 days, the specimens were oven dried at 105±5℃ to ensure a constant weight prior to the test. Water absorption was measured at 10, 30, 60 and 120 minutes after testing begin. The initial surface absorption rate is expressed in milliliters per square meter per second (ml/m^2-s).

Table 3 PSAI results

	Compressive strength (MPa)		
	7 days	28 days	91 days
Control mortar	28.48	35.90	42.83
Mortar containing rock wool wastes	19.51	29.44	44.13
PSAI (%)	69	82	103

The PSAI test was performed in accordance with ASTM C311-11. This test determines whether rock wool waste induces an acceptable level of strength development in concrete. The control mixture consisted of 1 part of Portland cement to 2.75 parts of graded aggregate by mass, with a water/cement ratio of 0.48. The cement was replaced by rock wool waste in the test mixture at a replacement level of 20 wt.%. The PSAI was then calculated as follows

$$\text{PSAI (\%)} = 100 \times (T/C) \quad (1)$$

where T is the average compressive strength of test mix cubes at curing ages of 7, 14, 28 and 56 days, and C is the average compressive strength of the control mix specimens at the same curing ages.

3. Results and discussion

3.1 Pozzolanic strength activity index

Table 3 shows the PSAI results of the mixtures containing rock wool waste. The PSAI values for rock wool waste specimens at 7, 28 and 91 days were 69%, 82% and 103%, respectively. At the age of 7 days, the PSAI was slightly lower than 75%. As the age increases, the PSAI increases significantly and the PSAI exceeded 75%, which is the minimum value required to classify a pozzolanic materials by ASTM C618. This indicates that the rock wool wastes can be classified as pozzolanic. Previous research (Cheng *et al.* 2011) shows that an increase in rock wool waste fineness effectively increases the PSAI and improves the compressive strength. Finer particles also enhance strength development.

3.2 Flow spread

Fig. 3 shows the flow spread of the mixtures containing rock wool waste. This figure shows that the flow spread increased as the amount of rock wool waste increased from 0% to 20%. However, the flow spread decreased as the amount of rock wool waste increased from 20% to 40%. The flow spread of AR30 and AR40 specimens was lower than the control specimens. This may be due to the cylindrical and fibrous shape of rock wool waste, and its highly porous textures, compared to that of cement (Fig. 2). The porous texture of rock wool waste increases the water demand and decreases the flow spread, thus decreasing workability. Thus, the flow spread results

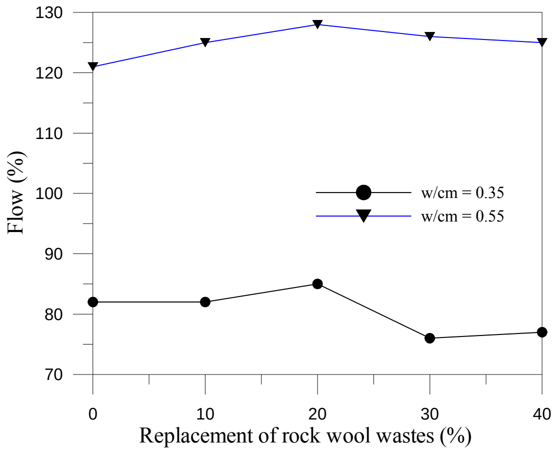


Fig. 3 Flow versus replacement of rock wool wastes curves

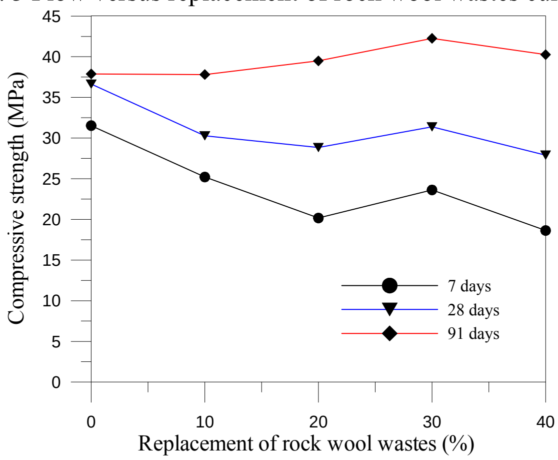


Fig. 4 Compressive strength versus replacement of rock wool wastes curves for mix A

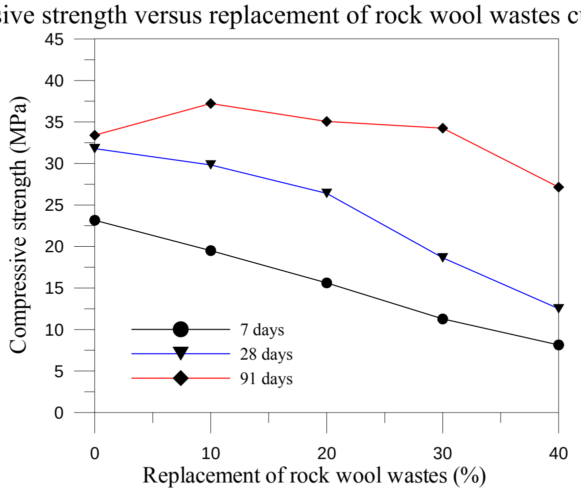


Fig. 5 Compressive strength versus replacement of rock wool wastes curves for mix B

suggest that a 20% addition of rock wool waste to cement is the optimal amount.

3.3 Compressive strength test

Figs. 4 and 5 show the compressive strength development curves of specimens with *w*/cm of 0.35 and 0.35, respectively. At the age of 7 and 28 days for both mixes, the compressive strength decreased as the rock wool waste content increased. The compressive strength of specimens containing rock wool wastes was about 20~40% lower than the control specimens. At the age of 91 days, the compressive strength increased as the rock wool waste content increased, except for BR40 specimens. In the later ages, the strength development increased obviously and the pozzolanic reaction grew rapidly. The trend of specimens containing rock wool wastes is similar to that is observed for the other pozzolans, such as fly ash (ACI 232.2R 2004). The increase in strength may be due to the pozzolanic reaction. This result also confirms that the pozzolanic reaction is small at an early age and increases in significance at a later age. Besides, the grain sizes of rock wool wastes used in this study are much smaller than 75 μm. From previous researches (Chai *et al*. 2011), this suggests that a small particle size increased the compressive strength of mortar and the filler effect of larger particles caused a reduction in the compressive strength of mortar compared to smaller particles. In addition, an appropriate arrangement of the small particles contributed to the compressive strength through the filler effect (Detwiler and Mehta 1989, Goldman and Bentur 1993). This finding agrees with previous research regarding bagasse ash and other pozzolanic materials (Bhanja and Sengupta 2002, TFairbairn *et al.* 2010, Khan and Alhozaimy 2011). Based on the test results mentioned above, the inclusion of 30% and 10% rock wool waste is the optimal limit for lower and higher *w*/cm, respectively.

3.4 Dry shrinkage test

Figs. 6 and 7 present the drying shrinkage results calculated for specimens containing rock wool waste at the age of 4, 11, 18 and 25 days. At the age of 4 days for the lower *w*/cm, the drying shrinkage value of the specimens containing rock wool waste was higher than that of the control specimens. At the age of 11 days, the drying shrinkage value of the specimens containing rock wool waste was lower than that of the control specimens and the AR30 specimens had the lowest value. The AR10 and AR20 specimens were similar to the control specimens. For the higher *w*/cm, the drying shrinkage value of the specimens containing rock wool waste was lower than that of the

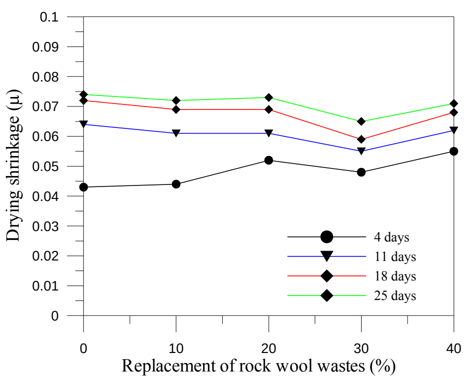


Fig. 6 Drying shrinkage versus replacement of rock wool wastes curves for mix A

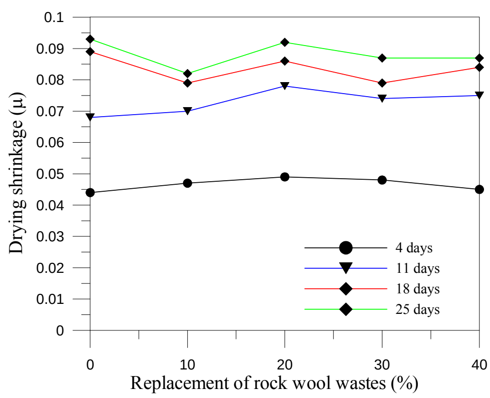


Fig. 7 Drying shrinkage versus replacement of rock wool wastes curves for mix B

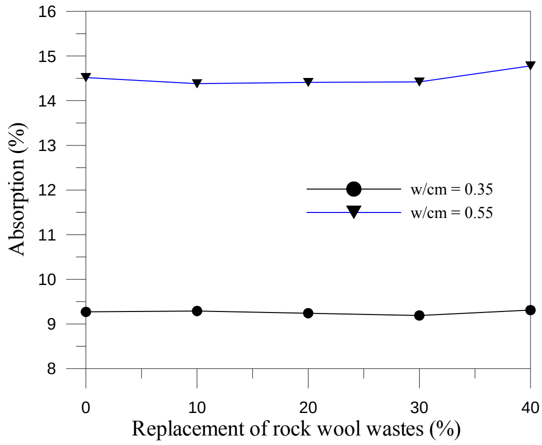


Fig. 8 Absorption versus replacement of rock wool wastes curves

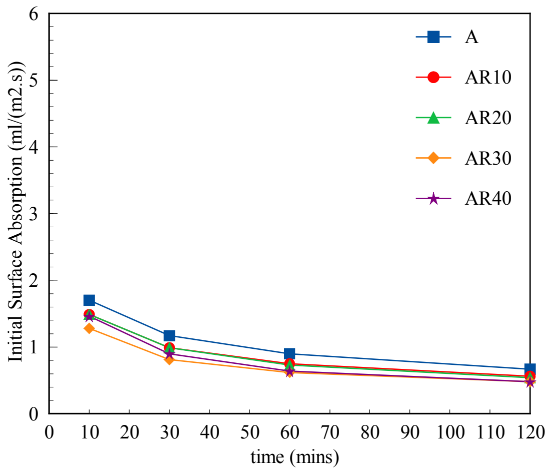


Fig. 9 Initial surface absorption curves for mix A

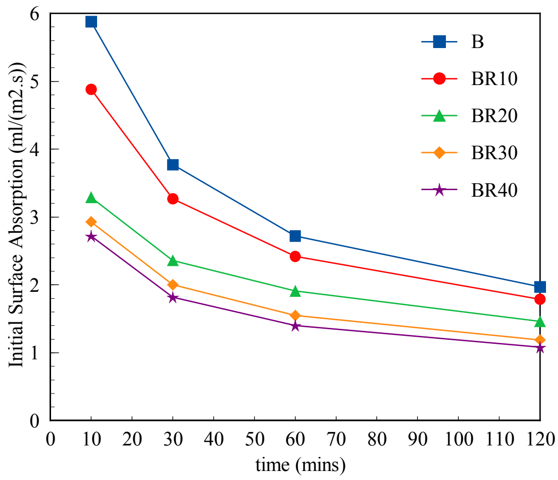


Fig. 10 Initial surface absorption curves for mix B

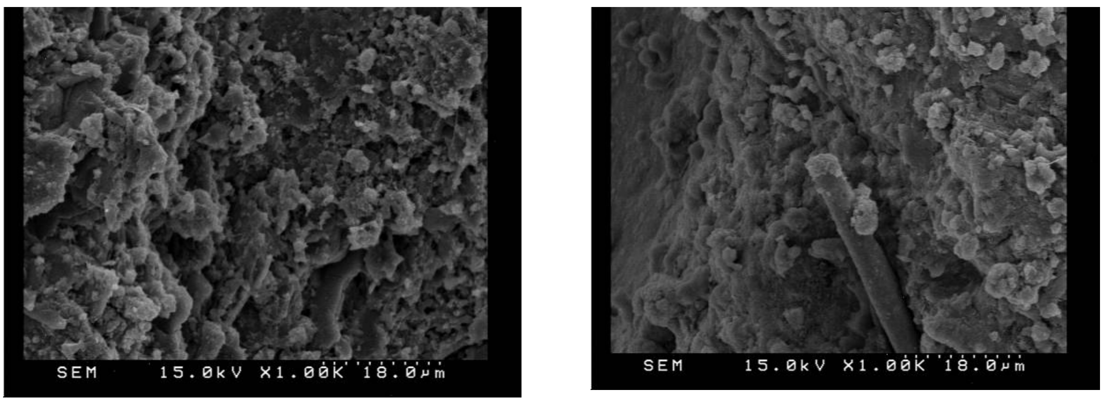
control specimens at the age of 18 days. The BR10 specimens had the lowest value, and decreased by up to 12% compared to the control specimens. The cylindrical and fiber particles of rock wool waste can arrest crack propagation and reduce the dry shrinkage, as illustrated in Fig. 2. This finding is consistent with previous research (Cheng *et al.* 2011).

3.5 Absorption test

Fig. 8 shows the absorption of the cement-based composites containing rock wool wastes. This figure shows that increasing the rock wool waste content has an insignificant influence on absorption for both mixes. The difference in absorption is primarily due to the lower *w*/cm. The absorption of specimens decreased as the *w*/cm decreased.

3.6 Initial surface absorption test

Figs. 9 and 10 plot the variations of initial surface absorption with respect to testing time for the cement-based composites. These figures indicate that the initial surface absorption values of the specimens decreased with testing time, and reveal that increasing the rock wool waste content has a significant influence on initial surface absorption for the higher *w*/cm specimens. According to the Kumar's study (Kumar *et al.* 2004), the initial surface absorption (ISA) rate lower than 0.07 ml/m^{2}s at 120 minutes indicates low concrete permeation. When the ISA rate is between 0.07 to 0.15 ml/m^{2}s at 120 minutes, it indicates medium concrete permeation. An ISA higher than 0.15 ml/m^{2}s at 120 minutes indicates high concrete permeation. The ISA rate for all mixes in this study exceeded 0.5 ml/m^{2}s at 120 minutes, indicating a high degree of liquid permeability in all mixtures. However, the absorption of the AR40 and BR40 specimens decreased by 28 and 45%, respectively. The inclusion of rock wool waste in cement-based composites can effectively reduce the initial surface absorption, especially at a higher *w*/cm. This may be due to pozzolanic reaction between calcium hydroxide and reactive silica in rock wool waste as illustrated in Fig. 11. While irregular crystallike structures and several large pores were found on the surface of the control specimen, smooth surfaces and compact micro structures with no distinct pores were observed in the AR40 specimens. The addition of rock wool wastes may cause smaller sizes of capillary pores and



(a) A specimen (age=91 days, x1000) (b) AR40 specimen (age=91 days, x1000)

Fig. 11 SEM observation of specimens with and without rock wool particles

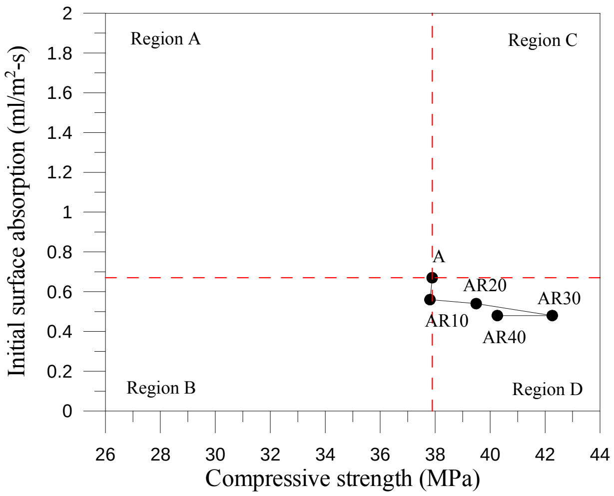


Fig. 12 Relationship between initial surface absorption and compressive strength for mix A

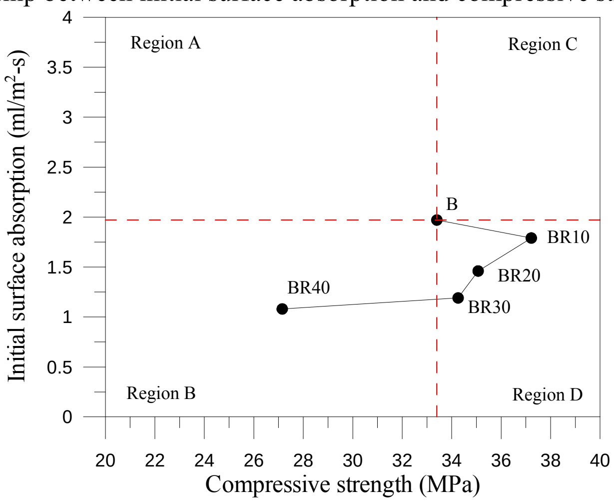


Fig. 13 Relationship between initial surface absorption and compressive strength for mix B

decrease the pore interconnectivity because the fiber-shape rock wool wastes could bridge cracks and arrest capillary pores. Thus, the addition of rock wool waste reduces permeable voids.

Based on the studies reported by Chusilp and Lee (Chusilp *et al.* 2009, Lee *et al.* 2012), the compressive strength and initial surface absorption can be considered as key indices to evaluated the durability. The relationship between initial surface absorption and compressive strength of rock wool waste specimens for mix A and B are illustrated in Figs. 11 and 12, respectively. The figures are divided into four regions. The region A, B, C and D represent the composites with lower compressive strength and higher absorption, lower compressive strength and lower absorption, higher compressive strength and higher absorption, and higher compressive strength and lower absorption, respectively. The specimens containing rock wool wastes are located in region D. Those specimens reflected higher compressive strength and lower permeability, which validates the pozzolanic and filling effect. In addition, the initial surface absorption decreased with an increasing of rock wool wastes. Inclusion of 30% and 10% rock wool wastes in cement-based composites had the highest compressive strength for lower and higher *w*/cm ratio, respectively, which confirmed the optimal amount achieved the best performance.

4. Conclusions

This study shows that it is feasible to utilize rock wool waste as a partial replacement of cement in cement-based composites. The PSAI results in this study show that the PSAI is 103% for rock wool waste specimens at the age of 91 days. The fine particles in rock wool waste (less than 75 μm) play an important role in its ability cementitious capability due to hydration or pozzolanic reactions. The addition of rock wool waste to cement-based composites decreased the dry shrinkage and initial surface absorption and increased the compressive strength. Specimens with 30% and 10% rock wool waste as a cement replacement achieved the best performance on compressive strength and initial surface absorption for 0.35 and 0.55 *w*/cm specimens, respectively. The inclusion of 20% rock wool waste in composites resulted in higher flow spread than the control specimens. However, the flow spread decreased when the replacement percentage exceeded 20%. The addition of rock wool waste to cement composites had an insignificant influence on absorption.

References

ACI Committee 232 (2000), "Use of raw or processed natural pozzolans in concrete (ACI 232.1R-00)", Farmington Hills: American Concrete Institute.

ACI Committee 233 (2001), "Ground, granulated blast furnace slag as a cementitious constituent in concrete (ACI 233R-95)", ACI manual of concrete practice, part 1. Farmington Hills: American Concrete Institute.

ACI Committee 232 (2004), "Use of fly ash in concrete (ACI 232.2R-03)", ACI Manual of concrete practice, part 1. Farmington Hills: American Concrete Institute.

ACI Committee 234 (2006), "Guide for use of silica fume in concrete (ACI 234R-06)", ACI manual of concrete practice, part 1, Farmington Hills: American Concrete Institute.

Bhanja, S. and Sengupta, B. (2002), "Investigations on the compressive strength of silica fume concrete using statistical methods", *Cement Concrete Res*., **32**(9), 1391-1394.

Chai, J., Jatuphon, T., Sawang, S. and Kraiwood, K. (2011), "Filler effect and pozzolanic reaction of ground palm oil fuel ash", *Constr. Build. Mater*., **25**(11), 4287-4293.

Cheng, A., Huang, R., Wu, J.K. and Chen, C.H. (2005), "Influence of GGBS on durability and corrosion behavior of reinforced concrete", *Mater. Chem. Phys*., **93**(2-3), 404-411.

Chen, C.H., Huang, R., Wu, J.K. and Yang, C.C. (2006), "Waste E-glass particles used in cementitious mixtures", *Cement Concrete Res*., **36**(3), 449-456.

Cheng, A., Lin, W.T. and Huang, R. (2011), "Application of rock wool waste in cement-based composites", *Mater. Des*., 32(2), 636-642.

Chusilp, N., Jaturapitakkul, C. and Kiattikomol, K. (2009), "Utilization of bagasse ash as a pozzolanic material in concrete", *Constr. Build. Mater*., **23**(11), 3352-3358.

Detwiler, R.J. and Mehta, P.K. (1989), "Chemical and physical effects of silica fume on the mechanical behavior of concrete", *ACI Mater. J*., **86**(6), 609-614.

Goldman, A. and Bentur, A. (1993), "The influence of microfillers on enhancement of concrete strength", *Cement Concrete Res*., **23**(4), 962-972.

Kumar, R. and Bhattacharjee, B. (2004), "Assessment of permeation quality of concrete through mercury instruction porosimetry", *Cement Concrete Res*., **34**(2), 321-328.

Khan, M.I. and Alhozaimy, A.M. (2011), “Properties of natural pozzolan and its potential utilization in environmental friendly concrete”, *Can. J. Civil Eng*., **38**(1), 71-78.

Lee, C.L., Huang, R., Lin, W.T. and Weng, T.L. (2012), “Establishment of the durability indices for cement-based composite containing supplementray cementitious materials”, *Mater. Des*., **37**(5), 28-39.

Lin, W.T., Huang, R., Lee, C.L. and Hsu, H.M. (2008), “Effect of steel fiber on the mechanical properties of cement-based composites containing silica fume”, *J. Mar. Sci. Technol*., **16**(3), 214-221.

Lin, W.T., Huang, R., Chang, J.J. and Lee, C.L. (2009), “Effect of fiber on the permeability of cement-based composites containing silica fume”, *J. Chin. Inst. Eng*., **32**(4), 531-541.

Milena, J. and Robert, C. (2006), “Effect of hydrophilic admixtures on moisture and heat transport and storage parameters of mineral wool”, *Constr. Build. Mater*., **20**(6), 425-434.

Nuclear power plants low level radioactive waste storage status (2011), *Fuel cycle and materials administration*, Taiwan.

Premur, V. and Salopek, B. (2004), “Recycling of waste mineral wool: REWAS’04 – global symposium on recycling”, *Waste Treat. Clean Technol. Proc*., 2789-2790.

Ramachandran, V.S. and Beaudoin, J.J. (2001), “Handbook of analytical techniques in concrete science and technology: principles, techniques and applications”, 1st ed. William Andrew.

TFairbairn, E.M., Americano, B.B., Cordeiro, G.C., Paula, T.P., Toledo, Filho, R.D. and Silvoso, M.M. (2010), “Cement replacement by sugar cane bagasse ash: CO2 emissions reduction and potential for carbon credits”, *J. Environ. Manage*., **91**(9), 1864-1871.

Wei, M.S. and Huang, K.H. (2001), “Recycling and reuse of industrial waste in Taiwan”, *Waste. Manage*., **21**(1), 93-97.

Wang, C.C. (2003), “Thermal plasma vitrification of low-level radioactive waste surrogates from nuclear power plants”, Master thesis, Institute of Materials Engineering, National Taiwan Ocean University, Taiwan.

Yearbook of environmental protection statistics Taiwan Area (2010), *Environmental protection administration*, Taiwan.

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