Ph. D. Thesis

Strength Properties of Eco-mortar Made with Oyster Shell Aggregate and Ground Granulated Blast Furnace Slag and Application to Pavement Material

(かき殻骨材と高炉スラグ微粉末を用いたエコモルタルの強度特性と舗装材料への適用)

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Abstract

In recent years steel industry by-products and waste shell management become real challenge due to their large amount, expensive management system and adverse effects on environment. On the other hand the demands of the construction materials are increasing day by day. Eco-mortar (made with recycled aggregate and eco-binder) which has positive relation with reduction of environmental hazards can play a vital role to save the environment and to continue the present construction activities.

The present study was an attempt to elucidate the effects of ground granulated blast furnace slag (GGBFS) as partial replacement of ordinary Portland cement (OPC) and oyster shell (OS) aggregate blended mortar on the strength properties in different conditions and the effective use as pavement material. To know the effective usability of the study materials, brightness, light irradiation in control and open natural condition, spectrometric analysis and skid resistance test performed. Cylindrical samples (ϕ 5 cm × 10 cm) were used for the compressive strength test at 3, 7, 28 and 91 days. Blended mortar was top filled on open graded asphalt concrete (30 cm × 30 cm × 5 cm) with about 1 cm thickness by the help of vibrator. Total six types of mortar filled pavement were used for brightness, light irradiation and skid resistance test to compare with asphalt concrete pavement.

Slag could be used up to 85% as partial replacement of cement and 75% slag content will give the highest strength for OS mortar. The compressive strength of river sand (RS)-slag mortar could be lowered at initial stage but finally will increase about 17% for 50% slag content than that of no slag mortar. At 28 days age, 30℃ water curing samples showed the highest strength for river sand mortar samples, and 20℃ water curing showed the highest compressive strength for OS mortar samples. Comparatively higher temperature is preferable for the high early strength of GGBFS blended mortar.

In brightness, light irradiation test and spectrometric analysis showed that ordinary Portland cement (OPC)-Slag-OS sample is the brightest and highest solar reflector as well as it showed lowest surface temperature within the study pavements. OPC-Slag-OS blended mortar inserted pavement reduced highest surface temperature (16℃) in compare with asphalt pavement. In terms of skid resistance property in wet condition, OS mortar filled pavement could be used in walkways, parking area and other suitable sites. Slag blended Eco-mortar could be used in pavement construction.

Chapter 1

Introduction

1.1 Background of the Study

In recent years, industrial and construction wastes become a big problem because of their risky and expensive management system. On the other hand the demands of the construction materials are increasing day by day for the growing construction industry. Aggregates (coarse and fine aggregates) and binders are the most important materials for the concrete as well as construction works. The source of the aggregates and the raw-materials of the binder product is natural mine. The mining activity is creating pressure on environmental sustainability which is causing vulnerable condition for the future. To save the environment and to continue the present construction in the world use of recycled construction aggregates and replacing traditional binder can play a vital role in this regards. For safe and sustainable use of the recycled aggregates in construction industry, more and more research work is the demand.

1.2 What About the Cement Production, Uses and Related Environmental Issues?

1.2.1 Why Cement is Producing and Using Worldwide as a Binder Material?

Cement is considered one of the most important building materials around the world. It is mainly used for the production of concrete. Concrete is a mixture of inert mineral aggregates, e.g. sand, gravel, crushed stones, and cement. Cement consumption and production is closely related to construction activity, and therefore to the general economic activity. Cement is one of the most produced materials around the world. Due to the importance of cement as a construction material, and the geographic abundance of the main raw materials, i.e. limestone, cement is produced in virtually all countries [1].

1.2.2 What is the Amount of Cement Production worldwide?

Globally, over 150 countries produce cement and/or clinker, the primary input to cement. In 2001, the United States was the world's third largest producer of cement (90 million metric tons (MMt)), behind China (661 MMt) and India (100 MMt) [2].

1.2.3 What is the Demand of the Cement Industries for Production Other Than the Raw-materials?

Cement production is a highly energy intensive production process. The energy consumption by the cement industry is estimated at about 2% of the global primary energy consumption, or almost 5% of the total global industrial energy consumption. Due to the dominant use of carbon intensive fuels, e.g. coal, in clinker making, the cement industry is also a major emitter of CO_2 emissions. Besides energy consumption, the clinker making process also emits CO_2 due to the calcining process. [1].

1.2.4 What are the Impacts of Cement Production on the Environment?

The cement industry contributes about 5% to global anthropogenic CO_2 emissions. CO_2 is emitted from the calcination process of limestone, from combustion of fuels in the kiln, as well as from power generation. Estimated total carbon emissions from cement production in 1994 were 307 million metric tons of carbon (MtC), 160 MtC from process carbon emissions, and 147 MtC from energy use. Overall, the top 10 cement-producing countries in 1994 accounted for 63% of global carbon emissions from cement production. The average intensity of carbon dioxide emissions from total global cement production is 222 kg of C/t of cement. Emission mitigation options include energy efficiency improvement, new processes, a shift to low carbon fuels, application of waste fuels, increased use of additives in cement making, and, eventually, alternative cements and CO_2 removal from flue gases in clinker kilns [3].

1.2.5 What are the Solutions in this Regards?

We have to continue the construction activities as well as to stop or reduce the CO_2 production and emission. If we want to reduce the CO_2 production from cement industry, we have to reduce the production of cement which will make a crisis in construction sector. So, we have to find out a new material which will be acceptable from the engineering points of view as the complete or partial replacement of cement also will produce less or no CO_2. Ground granulated blast furnace slag (GGBFS) would be use as the partial replacement of cement.

1.2.6 What is the Ground Granulated Blast Furnace Slag?

Blast furnace slag is recovered by melting separation from blast furnaces that produce molten pig iron. It consists of non-ferrous components contained in the iron ore together with limestone as an auxiliary materials and ash from coke. Approximately 290 kg of slag is generated for each ton of pig iron. When it is ejected from a blast furnace, the slag is molten at a temperature of approximately 1,500℃. Depending on the cooling method used, it is classified either as air-cooled slag or granulated slag [4].

1.2.7 What is the Impact of Ground Granulated Blast Furnace Slag Use on the Environment?

Expanding the use of Portland blast furnace slag cement is one measure included in the plan to achieve the targets of the Kyoto Protocol, and there are large expectations for its ability to help reduce CO_2emissions. Under the Kyoto Protocol, Japan has made a commitment to the world to reduce its emissions of greenhouse gases by 6% from 1990 levels. The plan for achieving this public commitment includes a reduction in CO_2 emissions of 1.12 million tons resulting from a 16% increase in the production ratio of blended cement (FY 2004 result: 21.4% → FY 2010 planned value: 24.8%). The majority of the blended cement that is produced in Japan is Portland blast furnace slag cement. If we were to assume that Portland blast furnace slag cement accounted for all of the 16% increase in the production ratio of blended cement, this would contribute to an annual reduction in CO_2 emissions of 640,000 tons. Specifically, the use of 20% Portland blast furnace slag cement in the construction of a single apartment complex would result in a per-household CO_2 reduction of approximately 1,200 kg. These effects have been recognized by the national government, local governmental organizations, and private companies, and there is growing momentum toward stopping global warming by expanding the use of Portland blast furnace slag cement [4].

1.2.8 Is the Ground Granulated Blast Furnace Slag Available for the Use?

In the financial year 2013 Japan produced 25,271 thousand tons of blast furnace slag and 18,640 thousand tons of that was used in only cement industry. Beside this, total 23,089 thousand tons of blast furnace slag was used in the civil construction related activities [4].

1.3 What About the Aggregate Production, Related Environmental Hazards and Solution?

1.3.1 What About the Aggregates?

For this study we considered only fine aggregates. Within all the traditional fine aggregates, sand is the most widely used fine aggregate. The source of the sand is mining which is not good for the environmental sustainability.

1.3.2 What are the Effects of Natural Aggregate Mining on the Environment?

Mining of natural aggregates, including both sand and gravel and crushed rock, represents the main source of construction aggregates used throughout the world. However, operations of mining, whether small or large scale, are inherently disruptive to the environment. Also mining of aggregate frequently generates land use conflicts in populated areas due to its negative externalities including noise, dust, truck traffic, pollution and visually unpleasant landscapes. It also can represent a conflict with competing land uses such as farming, especially in areas where high-value farmland is scarce and where post-mining restoration may not be feasible. As pointed out by social and environmental activists there are potential linkages between mineral resources and conflict and consequential underdevelopment [5].

1.3.3 What is the Solution of Aggregate Mining?

Oyster is a popular food in Japan, china, South Korea and many more countries. In every year they are producing a lot of oyster shell as waste material. Many research works have done for using oyster shell aggregate and it could be the replacement of sand as fine aggregate.

1.3.4 Actually How Much Oyster Shell is Producing in Japan?

The production of oyster in Hiroshima prefecture was about 60% in Japan, oyster shell of about 100,000t was produced as a by-product. At this time, oyster shell has utilized as a fertilizer and a feed, but the amount of utilization of oyster shell has not been great [6].

1.4 Point of Research

There is many more research works already have conducted on oyster shell aggregate and grind granulated blast furnace slag. All the conducted research work was based on either oyster shell aggregate with traditional binder materials or slag with traditional aggregates. In this study we tried to conduct research activities with combination of slag as a partial replacement of traditional binder cement as well as oyster shell aggregate as the complete replacement of traditional aggregate sand and to compare the results with different selected combination of the aggregates and binder. We also tried to investigate the usability of the materials to pavement construction and to find out the best combination for this purpose.

1.5 Objectives of the Study

To investigate the following effects of slag content in mortar as a partial replacement of cement:

i. Effect of binder aggregate mixing ratio on compressive strength

ii. General effect of slag on compressive strength

iii. Effect of different percentage of slag on compressive strength

iv. Effect of slag on river sand mortar strength

v. Effect of slag on compressive strength development of (RS) and oyster shell (OS) mortar

vi. Effect of fineness of slag on OS mortar strength

vii. Effect of cement Types on OS mortar strength

viii. Effect of aggregate types on compressive strength

ix. Effect of super plasticizer on OS mortar strength

To investigate the following effects of curing temperature, air and water curing on mechanical properties (strength) of prepared mortar to find out the most suitable curing condition of the recycled aggregate and mineral (slag) mortar:

i. Strength of OPC-RS mortar with no slag content

ii. Strength of white Portland cement (WPC)-RS mortar with no slag content

iii. Strength of OPC-RS mortar with 50% slag content

iv. Strength of OPC-OS mortar with no slag content

v. Strength of high early strength Portland cement (HSPC)-OS mortar with no slag content

vi. Strength of OPC-OS mortar with 75% slag

To investigate the effective usability of the experimental aggregates for surface heat reduction of asphalt concrete by:

i. the brightness of the sample pavement surfaces

ii. the effect of light irradiation on pavement surface temperature in inside and controlled condition

iii. the effect of light irradiation on pavement bottom temperature in inside and controlled condition

iv. the effect of light irradiation on pavement surface temperature in open and natural weather condition

v. the spectrometric analysis for asphalt and filling mortar

vi. the skid resistance test of the study mortar filled pavements.

Chapter 2

Effects of Ground Granulated Blast Furnace Slag on Compressive Strength of Oyster Shell Aggregate Mortar

2.1. Introduction

To protect the global environment, there are growing demands from environmental organizations` in the world for recycling the construction materials, minerals and other ingredients to reduce environmental hazards. Researchers` are trying to increase the use of slag products in the construction industry not only as replacements for natural resources, but also as sustainable construction works.

In the financial year 2012 Japan produced 24,639 thousand tons of blast furnace slag and 72.6% of that was used in cement industry [**4**].

Replacing Portland cement with slag cement in concrete can save up to 59% of the embodied CO_2 emissions and 42% of the embodied energy required to manufacture concrete and its constituent materials [**7**].

In the USA, the levels of GGBFS (ground granulated blast furnace slag) replacements range from 25% to 50% for high strength concrete. In another study, it was found that slag replacement level of 40 to 60 % appeared to be the optimum level for high strength development. In Canada, the replacement level is about 50% for control of alkali-silica reaction. For concrete to resist sulphate attack and achieve a lower early age heat generation, the level of replacement will need to be within 60% to 85% for mass concrete construction. In China, the GGBFS replacement level usually ranges from 30% to 40% for optimum strength performance. In Hong Kong, the Tsing Ma Bridge adopted a replacement level of about 65% in order to meet the stringent durability requirements [**8**].

Many publications have reported the excellent performance of concrete containing mineral admixtures (MAs), such as ground granulated blast furnace slag (GGBFS) and pulverized fuel ash (PFA), in coastal marine environments [**9**].

The strength development of slag cement has a great consideration for the scheduling of formwork removal, prestressing operations, and other practical aspects of slag cement usage [**10**].

Fires can expose concrete to extreme temperatures. Thus, it is important to know the effect of elevated temperature on the concrete property. High performance concrete (HPC) often contains other supplemental cementitious materials besides cement, such as ground granulated blast furnace slag (GGBFS) and chemical admixtures such as super plasticizer (SP). GGBFS has been used successfully to improve concrete properties [**11**].

Large quantities of oyster shell (OS) are distributed globally. However, most OS ends up as industrial waste without being reused. To date, there is a shortage of natural fine aggregates. To solve these problems, OS can serve as a partial replacement of fine aggregate. Namely, concrete substituted with OS had a good engineering properties and showed high resistance against environmental attack [**12**].

WOS (waste oyster shell) sand can be resources of pure calcareous materials and effective in replacement of sand, indicating appropriate application of oyster shells, it is feasible to use in CLSM (controlled low-strength materials) [**13**].

Objectives of this study is to investigate the effect of slag content in mortar as a partial replacement of cement, to determine the optimum percentage of slag for sand and oyster shell (OS) mortar and to find out the specific effects of slag in sand and OS mortar.

2.2. Materials and Methods

2.2.1 Materials

(1) Slag

Ground granulated blast furnace slag (GGBFS) was used in this study (**Photo 2.1**). It was collected as steel industry by-product with specific chemical composition (**Table 2.1**). Three different particle sized slag were used with specific surface area of 4,000 cm^2/g, 6,000 cm^2/g, 8,000 cm^2/g and the density were 2.88 g/cm^3, 2.88 g/cm^3, 2.91 g/cm^3 respectively.

Photo 2.1 Ground granulated blast furnace slag

(2) Cement

Two types of cement were used in this study: Ordinary Portland cement (OPC) (**Photo 2.2**) with the density of 3.16 g/cm^3 and specific surface area of 3,290 cm^2/g. High early strength Portland cement (HSPC) (**Photo 2.3**) with the density of 3.14 g/cm^3 and specific surface area of 4,410 cm^2/g. Chemical constituents of cement is shown in **Table 2.2**.

Photo 2.2 Ordinary Portland cement

Photo 2.3 High early strength Portland cement

(3) Oyster Shell

The oyster shell (OS) (**Photo 2.4**) is a waste product produced from oyster farming. OS aggregate (**Photo 2.5**) collected from an oyster shell processing factory, Toba city, Japan. Collected material pulverized in crushed form with the density of 2.29 g/cm^3, maximum size of 2 mm and fineness modulus (F.M.) 2.27 filled in commercial bag. Chemical composition of OS aggregate is shown in **Table 2.3**.

Photo 2.4 Oyster shell

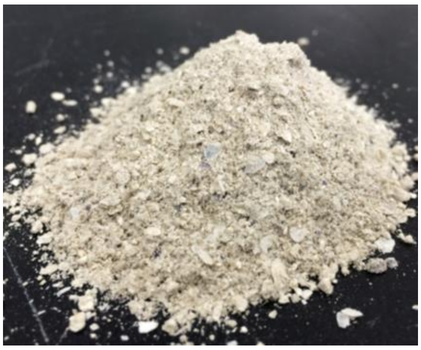


Photo 2.5 Oyster shell aggregate

The main chemical constituent of oyster shell is $CaCO_3$ and because of that it is using diversified field at present but that is not sufficient than its large quantity of production.

(4) Sand

River bed sand (**Photo 2.6**) was used in this study as a standard fine aggregate to compare the performance of other aggregates with it. Density of the used sand was 2.60 g/cm^3 and the fineness modulus (F.M.) was 3.13.

Photo 2.6 River bed sand

Table 2.1 Chemical composition of ground granulated blast furnace slag with different specific surface area

Chemical compositions (%)	S-40		S-60		S-80	
	JIS A 6205	Test value	JIS A 6205	Test value	JIS A 6205	Test value
Ignition loss	≤3.0	1.08	≤3.0	1.53	≤3.0	0.43
SiO_2	-	33.24	-	31.75	-	34.43
Al_2O_3	-	13.87	-	12.54	-	14.97
FeO	-	0.32	-	0.57	-	0.26
CaO	-	42.51	-	44.09	-	43.12
MgO	≤10.0	5.32	≤10.0	5.01	≤10.0	5.44
TiO_2	-	0.51	-	0.42	-	0.58
MnO	-	0.12	-	0.13	-	0.14
SO_3	≤4.0	1.92	≤4.0	3.37	≤4.0	-
Na_2O	-	0.20	-	0.18	-	0.27
K_2O	-	0.31	-	0.28	-	0.35
Cl^-	≤0.02	0.008	≤0.02	0.008	≤0.02	0.007

Table 2.2 Properties and constituents of cement used in the study

Chemical compositions (%)	OPC		HSPC	
	JIS R 5210	Test value	JIS R 5210	Test value
Ignition loss	≤5.0	2.26	≤3.0	1.02
SiO_2	-	20.45	-	20.42
Al_2O_3	-	5.24	-	4.98
Fe_2O_3	-	2.86	-	2.56
CaO	-	64.51	-	65.40
MgO	≤5.0	1.31	≤5.0	1.24
SO_3	≤3.5	2.16	≤3.5	2.94
Na_2O	-	0.24	-	0.20
K_2O	-	0.41	-	0.39
Cl^-	≤0.035	0.014	≤0.02	0.011

Table 2.3 Chemical composition of oyster shell aggregate

$CaCO_3$	N	P_2O_5	K	Mg	SiO_2	Fe	Mn
92.6%	0.09%	0.1%	0.03%	0.2%	0.48%	1.75ppm	66ppm

(5) Super Plasticizer

Super plasticizer (SP) was used to see its effect on OS mortar strength in without and with slag (S-40) condition. The main component of the SP was Polycarboxylic acid co-polymer. Appearance: Brown liquid. Density: 1.03-1.11 g/cm^3. Use limit: 0.1-4.0% of cement weight. In this study 1.5% SP was used to prepare sample.

The expressions of acronym used in this study are shown in **Table 2.4**.

Table 2.4 Expressions of acronym

Acronym	Original expression
OPC	Ordinary Portland cement.
HSPC	High early strength Portland cement.
S-0%, 50%, …...	Mortar with specific % of slag content.
S-40/Slag-40	Slag with specific surface area of 4,000 cm^2/g.
S-60/Slag-60	Slag with specific surface area of 6,000 cm^2/g.
S-80/Slag-80	Slag with specific surface area of 8,000 cm^2/g.
RS	River bed sand.
OS	Oyster shell aggregate.
GGBFS	Ground granulated blast furnace slag.
SP	Super plasticizer
W/B	Water binder ratio
1:2	Binder aggregate ratio 1:2
1:3	Binder aggregate ratio 1:3

2.2.2 Sample Preparation

Electronic digital balance was used to measure the mass of the experimental materials. An electric mixer machine (**Photo 2.7**) was used to mix the binder, aggregate and water to prepare mortar for the experiment.

The plastic mold (**Photo 2.8**) was used to cast the mortar block and it was collected from local supplier. The diameter of the casting mold was 50 mm and the height was 100 mm. For preparing the mortar at first the cement was mixed with the water for about 2 minutes and then the fine aggregates added and mixed for 3 minutes by the mortar mixing machine.

Photo 2.7 Fig. Mortar mixing machine

Photo 2.8 Mould used in the experiment

The flow test was performed to know the flow of the mortar according to the **JHS A 313**. Flow table, Flow mold, Caliper, Tamper, Trowel and straightedge (**Photo 2.9**) were used in this test. The dimensions of the flow mold were: Top and bottom diameter 80 mm, Height 80 mm. The test was performed at room temperature which was 20℃. The flow table/surface was cleaned, dried and wiped properly and the flow mold was placed at the center of the flow surface. A layer of mortar was placed in the mold about 40 mm in thickness and was gently tamped 20 times with the tamper. Then the rest of the portion of mold was filled with mortar and tamped 20 times like before. With the help of straightedge the top of the mold was make a plane surface. On the flow surface and around the edge of the flow mold especially water was cleaned and wiped very carefully. The mold was pulled from the mortar and the flow diameter was measured in four ways with calipers (**Photo 2.10**) and finally their average was taken for further calculation.

Mortar was prepared by different experiment materials with design mixing proportion (**Table 2.5**). Cylindrical samples (**Schematic view 2.1**) were prepared from mortar for the experiment with 50 mm diameter and 100 mm height (**Photo 2.11**).

Photo 2.9 Flow measuring instrument

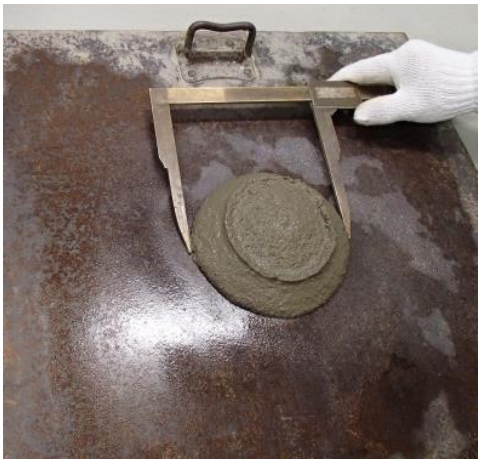
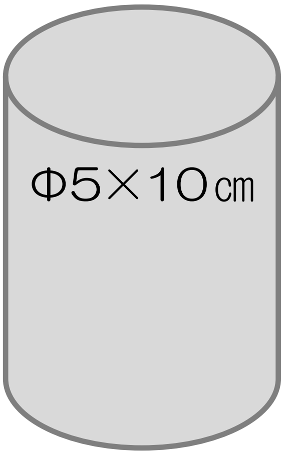


Photo 2.10 Flow measurement



Schematic view 2.1 Schematic view of the compressive strength test sample

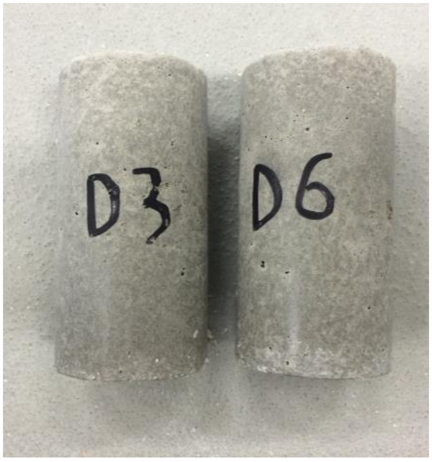


Photo 2.11 Compressive strength test sample

As slag was used as partial replacement of cement; cement and slag together was named as “Binder” in this study. Binder aggregate ratio was 1:2 and 1:3 for all cases. Different water binder ratios were determined by flow test to maintain the same workability and used to prepare the mortar. For oyster shell mortar; water binder ratio was 1.15 and 1.6 for 1:2 and 1:3 binder aggregate ratio respectively.   For River sand mortar; water binder ratio was 0.5 and 0.6 for 1:2 and 1:3 binder aggregate ratio respectively.

Table 2.5 Study mortar mix proportion (For 12 samples)

Sample	OPC (g)	slag (g)	RS	OS	SP	Water	W/B
	(binder, B)		(g)	(g)	(g)	(g)	
1:2 OPC OS	1,000	-	-	2,000	-	1,100	1.1
1:3 OPC OS	800	-	-	2,400	-	1,280	1.6
1:2 OPC 50%S-40 OS	500	500	-	2,000	-	1,150	1.15
1:2 OPC 50%S-60 OS	500	500	-	2,000	-	1,150	1.15
1:3 OPC 50%S-40 OS	400	400	-	2,400	-	1,280	1.6
1:3 OPC 50%S-60 OS	400	400	-	2,400	-	1,280	1.6
1:2 OPC 75%S-40 OS	250	750	-	2,000	-	1,150	1.15
1:2 OPC 75%S-60 OS	250	750	-	2,000	-	1,150	1.15
1:3 OPC 75%S-40 OS	200	600	-	2,400	-	1,280	1.6
1:2 OPC RS	1,800	-	3,600	-	-	900	0.5
1:3 OPC RS	1,200	-	3,600	-	-	720	0.6
1:2 OPC 50%S-40 RS	900	900	3,600	-	-	900	0.5
1:3 OPC 50%S-40 RS	600	600	3,600	-	-	720	0.6
1:2 OPC 75%S-40 RS	450	1,350	3,600	-	-	900	0.5
1:3 OPC 75%S-40 RS	300	900	3,600	-	-	720	0.6
1:2 OPC 50%S-80 OS	500	500	-	2,000	-	1,150	1.15
1:2 OPC 75%S-80 OS	250	750	-	2,000	-	1,150	1.15
1:2 HSPC OS	1,000	-	-	2,000	-	1,100	1.1
1:3 HSPC OS	800	-	-	2,400	-	1,280	1.6
1:2 OPC 85%S-40 OS	150	850	-	2,000	-	1,150	1.15
1:2 OPC 95%S-40 OS	50	950	-	2,000	-	1,150	1.15
1:3 OPC 85%S-40 OS	120	680	-	2,400	-	1,280	1.6
1:3 OPC 95%S.-40 OS	40	760	-	2,400	-	1,280	1.6
1:2 OPC OS	1,000	-	-	2,000	-	1,100	1.1
1:2 OPC 75%S-40 OS	250	750	-	2,000	-	1,150	1.15
1:2 OPC OS	1,000	-	-	2,000	-	1,100	1.1
1:2 OPC 75%S-40 OS	250	750	-	2,000	-	1,150	1.15
1:2 OPC OS 1.5% SP	1,000	-	-	2,000	15	850	0.85
1:2 OPC 75%S-40 OS 1.5% SP	250	750	-	2,000	15	880	0.88

2.2.3 Test Procedure

Compressive strength test was performed to know the ultimate compressive strength of the cylindrical mortar samples made with the selected materials. The compressive strength of the test aggregates mortar expressed as N/mm^2. Universal testing machine was used to determine the compressive strength test of the mortar block of the test aggregates. The load applied capacity of the universal strength testing machine was 0 kN to 500 kN with different load applied options.

Three cylindrical samples were used for each age of curing. Samples produced from study aggregates were demoulded after three days, then, samples were cured in water with 18 - 20℃ at 20℃ room temperature, until the samples were used for compressive strength measurement at 3, 7, 28 and 91 days. Compressive strength of each specimen was determined using universal testing machine with JIS A 1108 (**Photo 2.12**).

Photo 2.12 Photographic view of the compressive strength test by universal testing machine

Loading Rate Calculation:

Loading speed rate was determine by the following formula-

Loading rate = Area (A) x Standard loading speed (S)

Where, Area (A) = πr^2 [r is the radius of the study sample, which was 25 mm]

The standard loading rate is 0.6±0.4 $N/mm^2/sec$ and the maximum loading rate is 1 $N/mm^2/sec$ [**14**]

Therefore the estimated loading rate = (3.1415 x 25 x 25) x 1 [considering the maximum loading rate]

= 1963 x 1 N/sec

= 2 kN/sec or 10 kN/5sec or 20 kN/10sec

Compressive Strength Calculation:

Compressive strength was calculated by following formula-

Compressive Strength = P/A

Where,

P: Maximum applied load (N)

A: Cross sectional area of the loading surface (mm^2)

2.3 Results and Discussion

2.3.1 Mortar Flow Test Result

Though the mortar flow test result was not in the list of objective, it is very important for this study due to the new combination of the aggregate and binder material. The flow test value was maintained 100 mm to 120 mm for all the cases. To keep the flow value in this limit, water content was adjusted with different mixing ratio.

2.3.2 Effect of Binder Aggregate Mixing Ratio on Strength

Mixing proportions affected the strength of the mortar samples. The strength of the OS (**Fig.2.1** (**a**)) and RS (**Fig.2.1** (**b**)) mortar samples with binder-aggregate mixing ratio 1:2 was higher than the sample with mixing ratio 1:3 in all the test conditions.

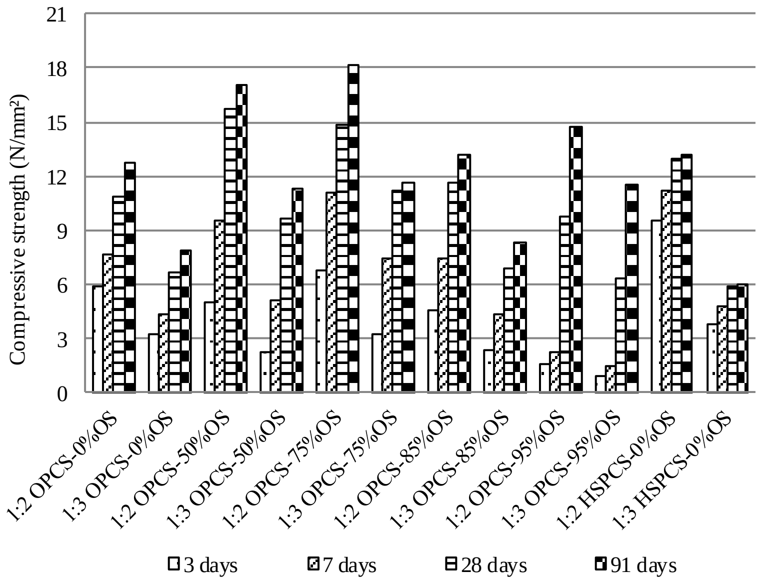


Fig.2.1 (**a**) Effect of mortar mix (1:2 and 1:3) ratio on strength of OS mortar

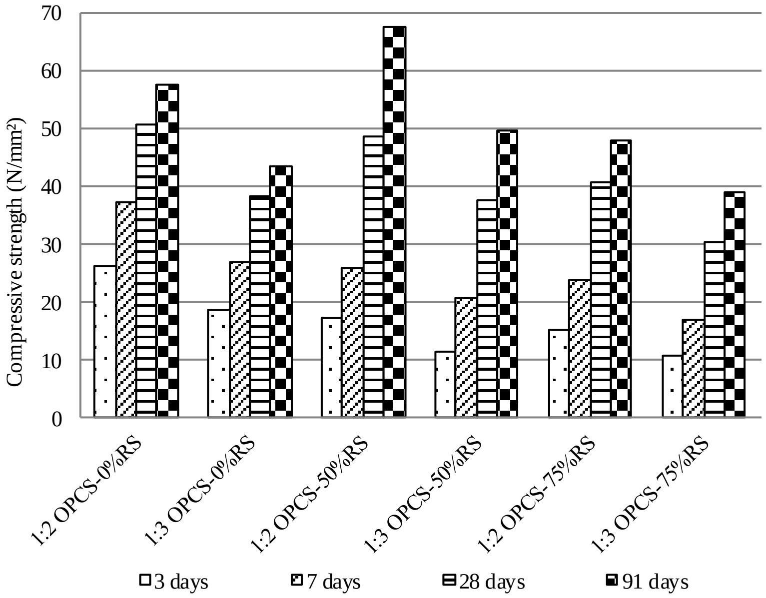


Fig.2.1 (**b**) Effect of mortar mix (1:2 and 1:3) ratio on strength of river sand mortar

2.3.3 General Effect of Slag on Strength

Generally recycled aggregates or byproducts have negative impact on the strength but slag content in mortar with partial replacement of cement showed positive effect on strength. The strength of mortar with slag content was gradually increased with time (3, 7, 28 and 91 days) shown in **Fig.2.2**. The strength of OS mortar at 91 days with 75% slag content was 42.1% increased than that of 0% slag content mortar.

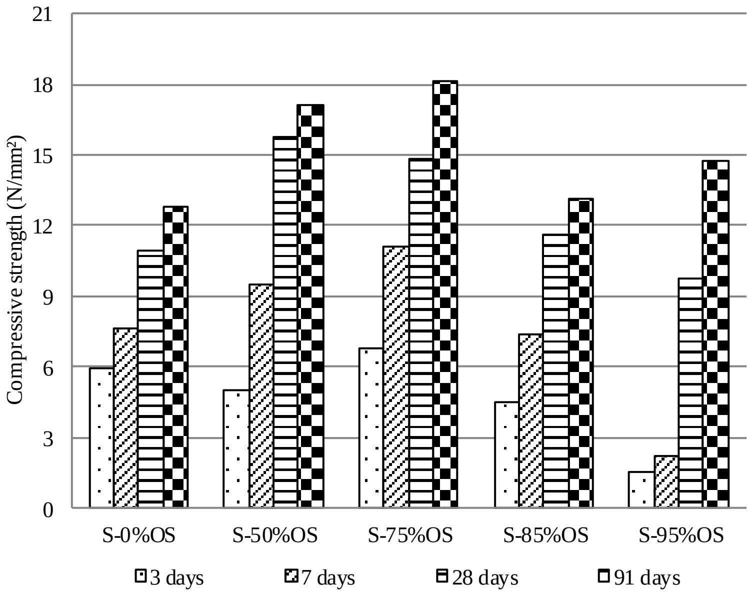


Fig.2.2 Primary effect of blast furnace slag (S-40) content on strength of OS mortar

GGBFS increase compressive strength within 28 days to 120 days [**15**]. The same result confirmed and reported that GGBFS improves workability and durability of concrete in [**11**]. Contributions of the mineral admixtures to performance improvement of the recycled aggregate concrete are higher than that to the natural aggregate concrete [**16**].

2.3.4 Effect of Different Percentage of Slag on Strength

The strength was highest in 75% of slag content and was gradually lowering trend with more or less content of slag in mortar shown in **Fig.2.3**.

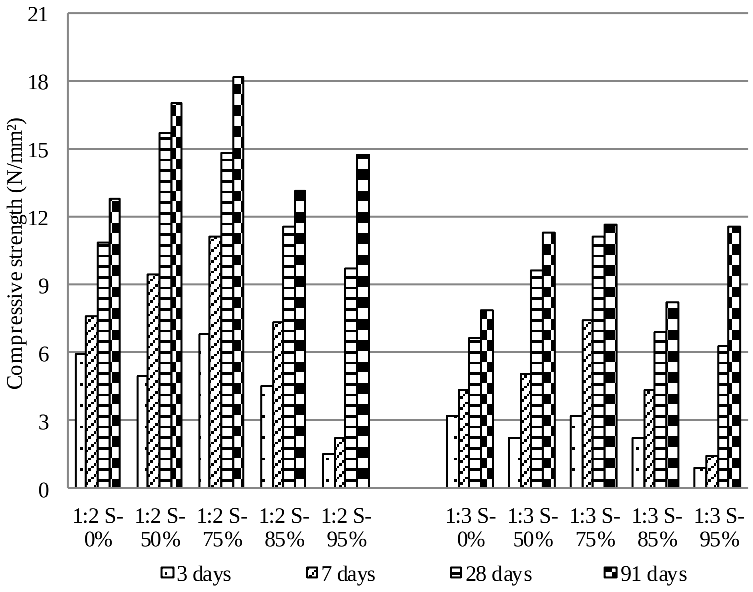


Fig.2.3 Variations of strength with different percentage of slag (S-40) in OS mortar

The trend of strength development was same with time except at 91 days result. The strength at 91 days was higher with slag content of 95% than that of 85%. So, the trend of strength development of slag used mortar will be stable up to 85% of slag content and 75% will give the best result. The strength development trend in slag-mortar with different mixing proportions (1:2 and 1:3) was same.

The compressive strength of the concrete increases up to 60% GGBFS containing as cement replacement [**15**]. The efficiency of the slag is similar to that of cement for 50% replacement rate [**10**]. The concrete mixtures composed of 50% and 70% slag presented minimal differences from the reference concrete, which was composed of 100% white Portland cement[**17**].

2.3.5 Effect of Slag on RS Mortar Strength

Strength of river sand (RS) mortar without slag content was higher than slag content mortar at early age (**Fig.2.4**). In 50% slag content mortar it was lower up to 28 days and was considerably higher (16.7%) than no slag mortar at 91 days. So, 50% slag content is preferable for RS mortar and will take time to gain expected strength.

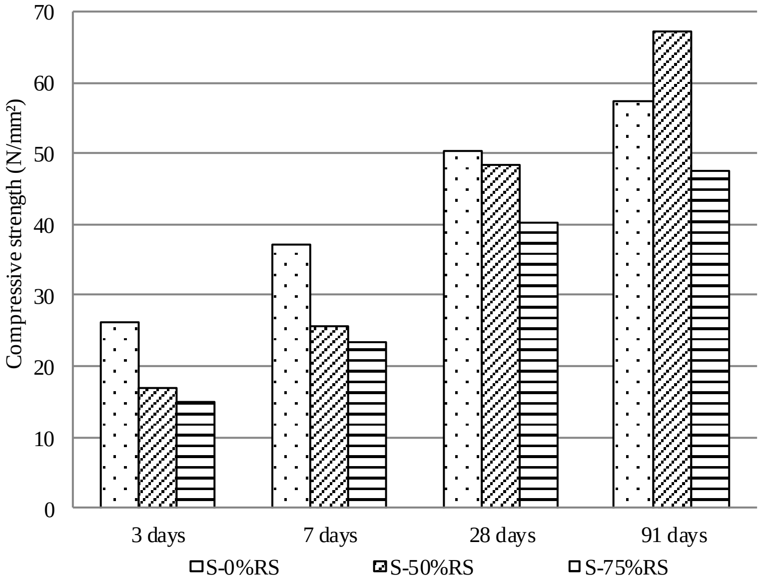


Fig.2.4 Effect of slag (S-40) content on the compressive strength of river sand mortar

The compressive strength increased with 50% slag replacement ratio with OPC [**18**]. Strength increased 10% with the 50% slag replacement ratio [**15**]. The compressive strength of slag concrete for 80% slag replacement ratio increased at satisfactory level [**19**].

2.3.6 Effect of Slag on Strength Development of RS and OS Mortar

In case of oyster shell (OS) mortar with 50% slag content, compressive strength was lowered only at three days test result in compare with the OS mortar with 0% slag. On the other hand the strength of river sand (RS) mortar was lower up to 28 days and at 91 days test result; it was 16.7% higher in compare with the RS mortar with 0% slag content shown in **Fig.2.5**. It indicates that the OS mortar with slag needs less time to gain the proper strength in compare with RS mortar with slag.

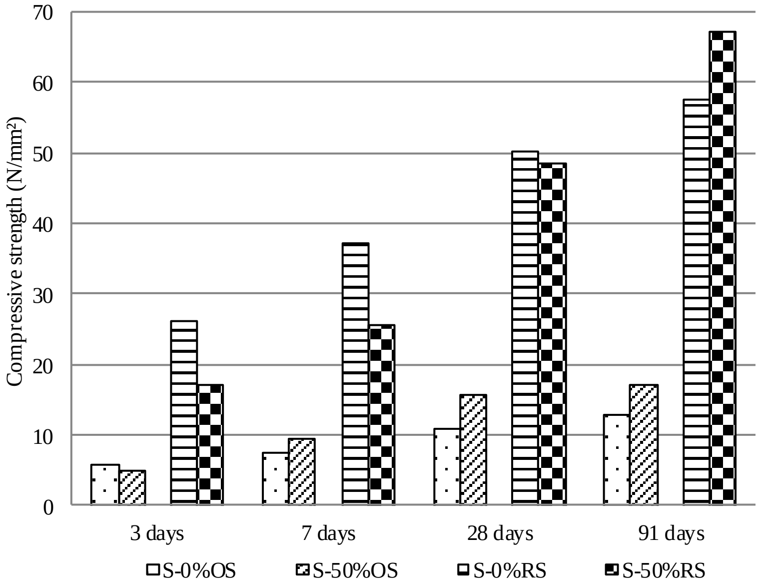


Fig.2.5 Effect of slag (S-40) content on strength development in RS and OS mortar

The compressive strength of high slag blast furnace cement (HBFC) concrete is inferior to that of the OPC concrete at all the curing period for the same design strength. This is primarily due to the slow hydration rate of the GGBFS in the HBFC concrete. But the differences in results between the two series concretes had decreased gradually with the increasing of curing period [**9**]

2.3.7 Effect of Fineness of Slag on OS Mortar Strength

Size or fineness of the slag has effect on the strength properties of mortar. Strength was increased with the fineness of the slag. The highest strength showed the sample with finest (8,000 cm^2/g) slag content (**Fig.2.6**). Generally slag means S-40 and it is the most available size in slag market, so it was used in other experiments though S-80 showed the highest strength. Same result found in [**10**].

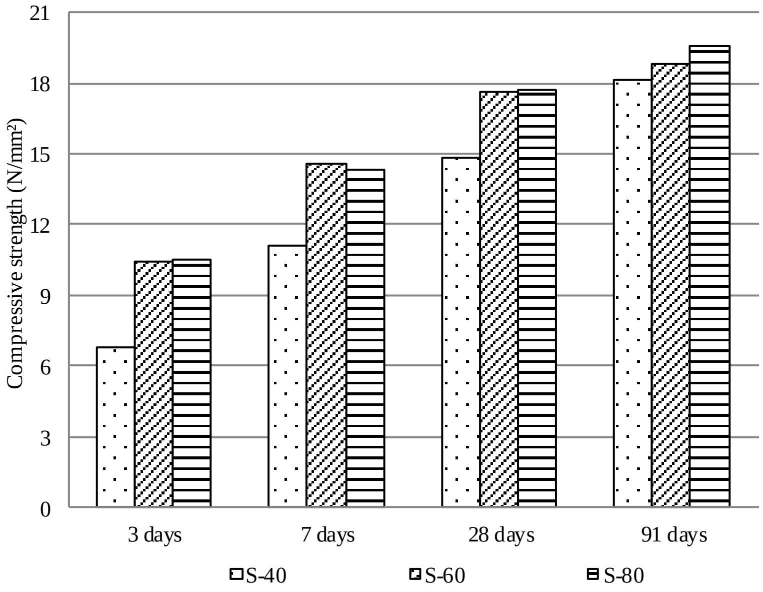


Fig.2.6 Effect of the fineness of slag (S-75%) on oyster shell mortar strength

2.3.8 Effect of Cement Types on OS Mortar Strength

High early strength Portland cement (HSPC) showed the higher compressive strength than ordinary Portland cement (OPC) for oyster shell aggregate mortar with 1:2 binder-aggregate mixing ratios. Mortar with 1:3 mixing ratio, OPC showed the initial lower strength and higher on later stage shown in **Fig.2.7**. It indicates that high early strength Portland cement in oyster shell mortar will give higher compressive strength with 1:2 mixing ratio and with 1:3 mixing ratio, lower strength on later age in compare with OPC.

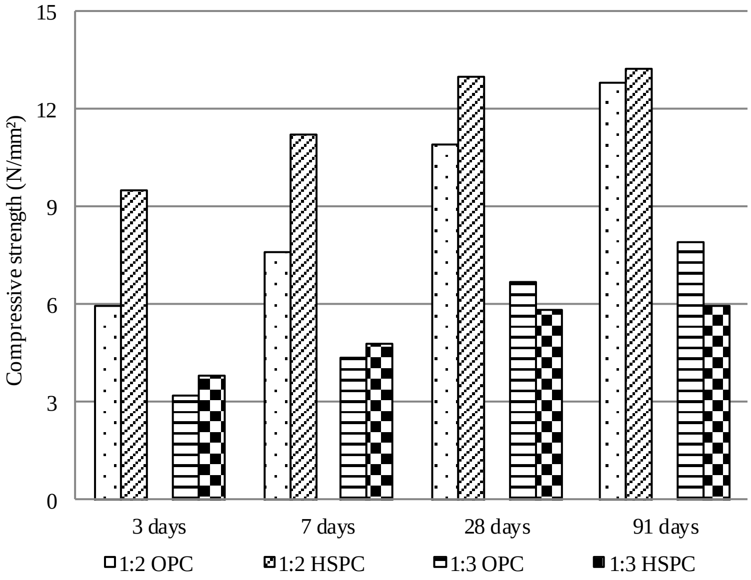


Fig.2.7 Effect of cement types on the strength of OS mortar with no slag content

2.3.9 Effect of Aggregate Types on Strength

Oyster shell aggregate has negative impact on strength of mortar as fine aggregate. OS mortar showed the lower strength in all cases in the study in compare with sand (**Fig.2.8**) due to the lower aggregate strength and density also for the contents of finer particle (0.075 mm).

Maximum strength reduction (81.71%) was observed for mortar with 0% slag content and with 1:3 mixing ratio. Minimum strength reduction (61.82%) was observed for mortar with 75% slag content and with 1:2 mixing ratio. So, the strength reduction due to the use of OS aggregate in replacement of sand in mortar could be reduced up to 20% by using slag in partial replacement of cement and the best result could be achieve by using 75% slag with 1:2 mixing ratio.

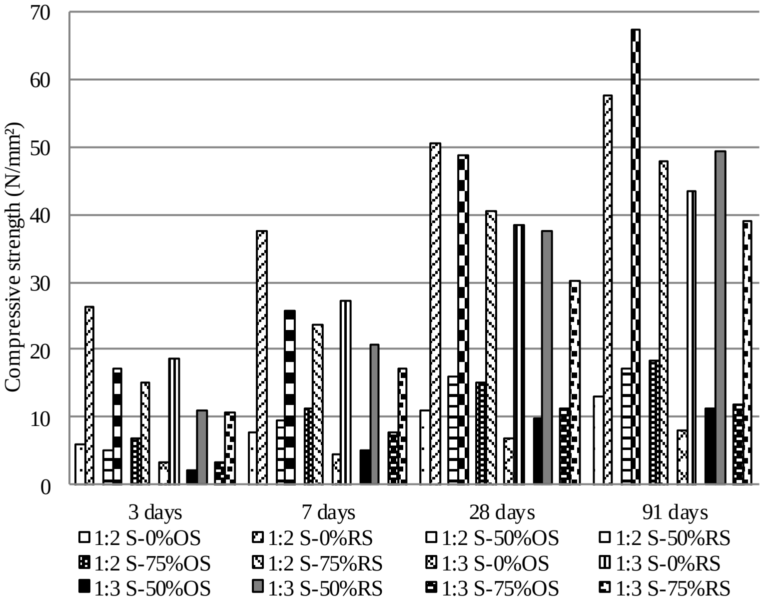


Fig.2.8 Effect of aggregate types (sand & oyster shell) on strength with and without slag (S-40) content

The substitution of oyster shell as a fine aggregate shows an insignificant effect on concrete compressive strength up to an age of 28 days. However, after 28 days, the effect is apparent [**12**]. Similar result found in [**20**]. There is no effect on compressive strength up to 20% of dosages of OS-sand instead of sand [**13**].

2.3.10 Effect of Super Plasticizer on OS Mortar Strength

OS-SP mortar with or without slag (S-40) content showed the higher strength at all ages than that of the mortar without SP is shown in **Fig.2.9**.

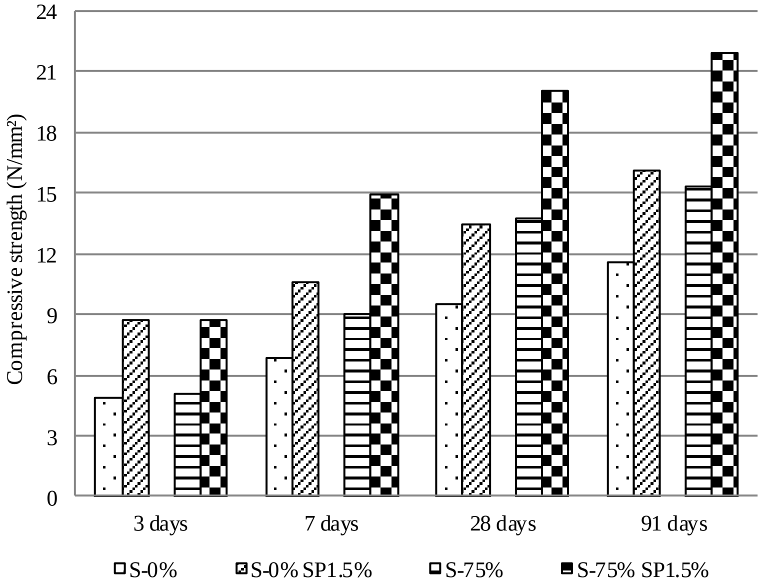


Fig.2.9 Effect of Super plasticizer on the strength of OS mortar in without and with slag content

Finally at 91 days OS-SP mortar with and without slag showed 43% and 40% higher strength respectively due to the decrease of water-binder ratio. The water-cement ratio decreased into 0.85 from 1.1 by the use of SP.

The same result found in [**21**]. Although the quantity of water and super plasticizer were different between the present and reference study, their impact was same on compressive strength in the both cases.

2.3.11 Density of the Mortar Sample

Density and compressive strength development pattern was almost same for the samples with the binder aggregate mixing ratio 1:2 and was opposite for binder aggregate mixing ratio 1:3. Density of the samples with binder aggregate mixing ratio 1:2 (**Fig.2.10**(**a**)) was increased with the increase of slag percentage up to 75 % then it was decreased with slag content 85% or more. On the other hand density of the samples with binder aggregate mixing ratio 1:3 (**Fig.2.10**(**b**)) was decreased with the increase of slag percentage up to 75% and was increased with slag content 855 or more. The cause of this different result is unknown.

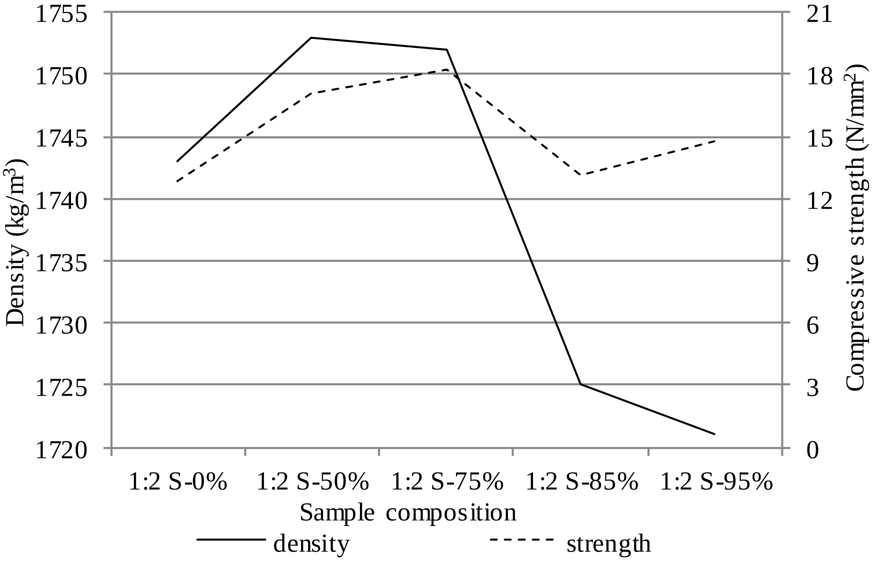


Fig.2.10(**a**) Density pattern of the mortar sample of binder aggregate mixing ratio 1:2

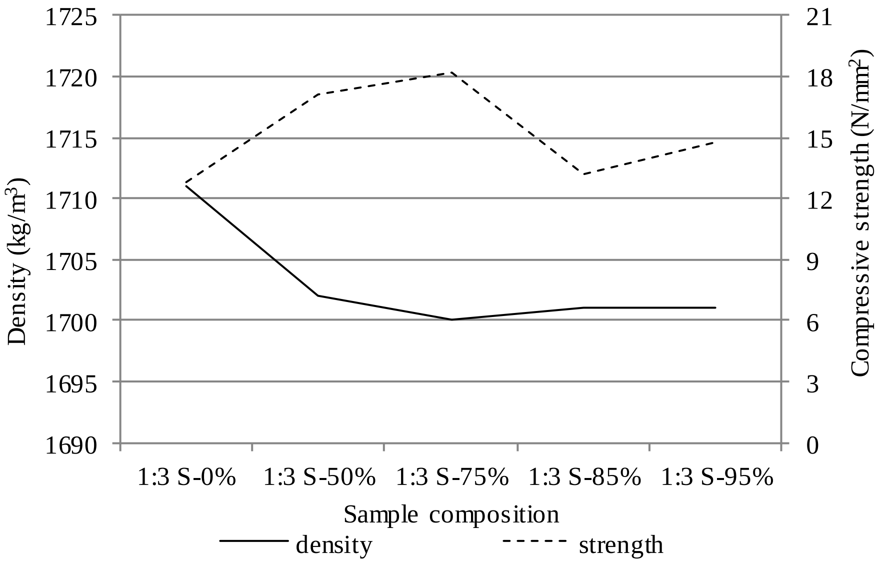


Fig.2.10(**b**) Density pattern of the mortar sample of binder aggregate mixing ratio 1:2

Density of the studied mortar samples were measured at every compressive strength test date and the result is shown in **Table 2.6**.

Table 2.6 Density (kg/m^3) of the mortar samples at different compressive strength test age

Sample	3 Days	7 Days	28 Days	91 Days
1:2 OPC OS	1,696	1,734	1,736	1,743
1:3 OPC OS	1,662	1,700	1,706	1,711
1:2 OPC 50%S-40 OS	1,696	1,728	1,785	1,753
1:2 OPC 50%S-60 OS	1,704	1,729	1,748	1,747
1:3 OPC 50%S-40 OS	1,646	1,684	1,692	1,702
1:3 OPC 50%S-60 OS	1,647	1,685	1,698	1,701
1:2 OPC 75%S-40 OS	1,709	1,739	1,730	1,752
1:2 OPC 75%S-60 OS	1,700	1,717	1,717	1,735
1:3 OPC 75%S-40 OS	1,649	1,687	1,686	1,700
1:2 OPC RS	2,217	2,234	2,233	2,250
1:3 OPC RS	2,202	2,225	2,218	2,238
1:2 OPC 50%S-40 RS	2,182	2,193	2,216	2,228
1:3 OPC 50%S-40 RS	2,188	2,217	2,212	2,228
1:2 OPC 75%S-40 RS	2,172	2,195	2,199	2,205
1:3 OPC 75%S-40 RS	2,181	2,200	2,190	2,205
1:2 OPC 50%S-80 OS	1,702	1,732	1,737	1,757
1:2 OPC 75%S-80 OS	1,697	1,718	1,718	1,737
1:2 HSPC OS	1,705	1,757	1,751	1,756
1:3 HSPC OS	1,618	1,647	1,660	1,666
1:2 OPC 85%S-40 OS	1,682	1,737	1,716	1,725
1:2 OPC 95%S-40 OS	1,673	1,726	1,711	1,721
1:3 OPC 85%S-40 OS	1,655	1,690	1,699	1,701
1:3 OPC 95%S.-40 OS	1,649	1,674	1,690	1,701
1:2 OPC OS	1,683	1,724	1,729	1,738
1:2 OPC 75%S-40 OS	1,700	1,734	1,737	1,747
1:2 OPC OS	1,639	1,463	1,437	1,435
1:2 OPC 75%S-40 OS	1,668	1,459	1,368	1,366
1:2 OPC OS 1.5% SP	1,551	1,640	1,643	1,672
1:2 OPC 75%S-40 OS 1.5% SP	1,641	1,651	1,697	1,691

2.4 Conclusions

The following conclusions can be drawn for S-40 (except the last conclusion number) used in the partial replacement of cement from the experimental results:

1) It would be wise to use the mixing ratio of cementing materials and fine aggregates 1:2 for oyster shell mortar with slag.
2) Slag have positive impact on compressive strength of mortar and it would be used up to 85% of slag content in partial replacement of cement and 75% slag content will give the best result.
3) The compressive strength of sand mortar with slag content could be lowered at initial stage but finally will increase at considerable rate.
4) The recommended amount of slag in RS mortar is 50% which will give higher strength than that of zero content mortar but will take time to get expected strength.
5) High early strength Portland cement (HSPC) in oyster shell mortar will give good result with 1:2 mixing ratio and less amount of use of HSPC have adverse effect on strength in compare with ordinary Portland cement (OPC).
6) Oyster shell aggregate has negative impact on strength of mortar as fine aggregate in compare with sand. The strength reduction due to the use of oyster shell aggregate for preparing mortar in replacement of sand could be reduced up to 20% by using slag in partial replacement of cement and the best result could be achieve by using 75% slag with 1:2 mixing ratio.
7) Oyster shell mortar strength could be increased by adding chemical additive such as super plasticizer (SP) with or without slag condition.
8) Fineness of the slag has effect on the strength properties of mortar. Finest the slag; highest the strength.

Chapter 3

Usability of Mortar Prepared by Oyster Shell Aggregate and Ground Granulated Blast Furnace Slag to Pavement Construction

3.1. Introduction

In Mie prefecture oyster farming is prospering and discharges a large quantity of oyster shell. Some of the shells are pulverized in factory after removing salt and utilized as an oyster shell [22].

WOS (waste oyster shell) sand can be resources of pure calcareous materials and effective in replacement of sand, indicating appropriate application of oyster shells, it is feasible to use in CLSM (controlled low-strength materials) [13].

In the financial year 2012 Japan produced 24,639 thousand tons of blast furnace slag and 72.6% of that was used in cement industry [4].

Nowadays, there is an increasing interest in the utilization of waste materials. In the case of construction industry there was a growing trend towards the development and use of waste as supplementary cementitious materials [23].

Asphalt concrete is a temperature dependent material that may fall within a category of materials defined as brittle or quasi-brittle particularly at subzero temperatures [24].

Bitumen starts behaving like a Newtonian fluid at temperatures ranging from 30 ℃ to 70℃. Above these temperatures, bitumen may start flowing through any possible crack open in the pavement, in a sort of capillary flow. This happens naturally when the temperature is high enough, for example during summer, although it can be also promoted artificially by induction heating or by microwave heating [25].

Cool pavements can be created with existing paving technologies (such as asphalt and concrete) as well as newer approaches such as the use of coatings or grass paving cool pavement technologies are not as advanced as other heat island mitigation strategies **[26]**.

Albedo is the percentage of incoming radiation reflected off a surface. An albedo of 1 means that 100% of incoming radiation is reflected (no radiation is absorbed); an albedo of 0 means that 0% of incoming radiation is reflected (all radiation is absorbed). Albedo of asphalt pavement is 0.05-0.10 and albedo for white Portland cement or pavement made with slag is 0.70-0.80 in new condition **[27]**.

Objectives of this study is to investigate the effect of curing temperature, air and water curing on mortar strength, to find out the most suitable curing condition of the recycled aggregate and mineral (slag) mortar and to the effective use of the experimental aggregates for surface heat reduction of asphalt concrete and to know the skid resistance properties of the studied mortar inserted pavements surface.

3.2. Materials and Methods

3.2.1 Materials

(1) Slag

In this study blast furnace slag (**Photo 2.1**) was used to measure the thermal heat reflectance due to its color and compare with the reflectance of other study materials. It was collected as steel industry by-product with specific chemical composition (**Table 3.1**). The slag was used with specific surface area of 4,000 cm^2/g and density 2.88 g/cm^3.

(2) Cement

Three types of cement were used in this study- Ordinary Portland cement (OPC) (**Photo 2.2**) with the density of 3.16 g/cm^3 and specific surface area of 3,290 cm^2/g;

high early strength Portland cement (HSPC) (**Photo 2.3**) with the density of 3.14 g/cm^3 and specific surface area of 4,410 cm^2/g and white Portland cement (WPC) (**Photo 3.1**) with the density of 3.05 g/cm^3 and specific surface area of 3,440 cm^2/g. WPC was used to measure the heat reflectance and to compare with the reflectance of slag due to their same color. Chemical constituents of cement are shown in **Table 3.2**.

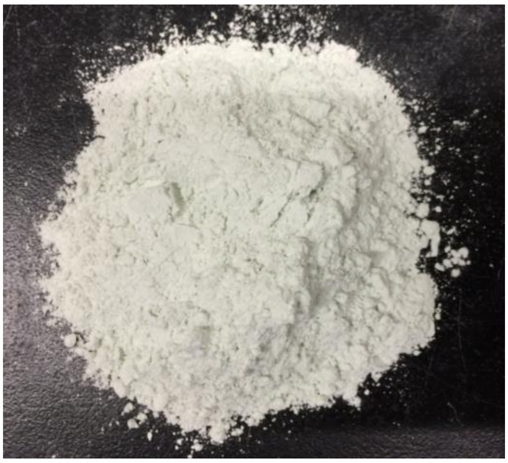


Photo 3.1 White Portland cement

(3) Oyster Shell

The oyster shell (**Photo 2.4**) is a waste product produced from oyster farming. Oyster shell aggregate (**Photo 2.5**) collected from an oyster shell processing factory, Toba city in Mie prefecture, Japan. Collected material pulverized in crushed form with the density of 2.29 g/cm^3 maximum size of 2 mm and fineness modulus (F.M.) 2.27 filled in commercial bag. Chemical composition of oyster shell aggregate is shown in **Table 2.3**.

(4) Sand

River bed sand (**Photo 2.6**) was used in this study as a standard fine aggregate to compare the performance of other aggregates with it. Density of the used sand was 2.60 g/cm^3 and the fineness modulus (F.M.) was 3.13.

(5) Asphalt Concrete

Open graded asphalt concrete pavement block (30cm × 30cm × 5cm) used in this study and collected from local source in Tsu, Japan. Asphalt pavement (**Photo 3.2**) was used as the base pavement and mortar was inserted on it by the help of vibrator.

Photo 3.2 Asphalt concrete pavement

Table 3.1 Chemical composition of ground granulated blast furnace slag

Chemical comp. (%)	Ig. loss	SiO_2	Al_2O_3	FeO	CaO	MgO	TiO_2	MnO	SO_3	Na_2O	K_2O	Cl^-
JIS A 6205	≤3.0	-	-	-	-	≤10.0	-	-	≤4.0	-	-	≤0.02
Test value	1.08	33.24	13.87	0.32	42.51	5.32	0.51	0.12	1.92	0.20	0.31	0.008

Table 3.2 Properties and constituents of cements used in the study

Chemical compositions (%)	OPC		HSPC		WPC	
	JIS R 5210	Test value	JIS R 5210	Test value	JIS R 5210	Test value
Ignition loss	≤5.0	2.26	≤3.0	1.02	≤5.0	3.13
SiO_2	-	20.45	-	20.42	-	22.46
Al_2O_3	-	5.24	-	4.98	-	4.60
Fe_2O_3	-	2.86	-	2.56	-	0.18
CaO	-	64.51	-	65.40	-	65.05
MgO	≤5.0	1.31	≤5.0	1.24	≤5.0	1.10
SO_3	≤3.5	2.16	≤3.5	2.94	≤3.5	2.77
Na_2O	-	0.24	-	0.20	-	0.06
K_2O	-	0.41	-	0.39	-	0.07
Cl^-	≤0.035	0.014	≤0.02	0.011	≤0.035	0.004

The expressions of acronym used in this paper are shown in **Table 3.3**.

Table 3.3 Expressions of acronym

Acronym	Original expression
OPC	Ordinary Portland cement.
HSPC	High early strength Portland cement.
WPC	White Portland cement.
RS	River bed sand.
OS	Oyster shell aggregate.
Slag	Ground granulated blast furnace slag.
Wc	Water curing.
Ac	Air curing temperature 20℃ and relative humidity 50-60%.
W/B	Water binder ratio.

3.2.2 Sample Preparation

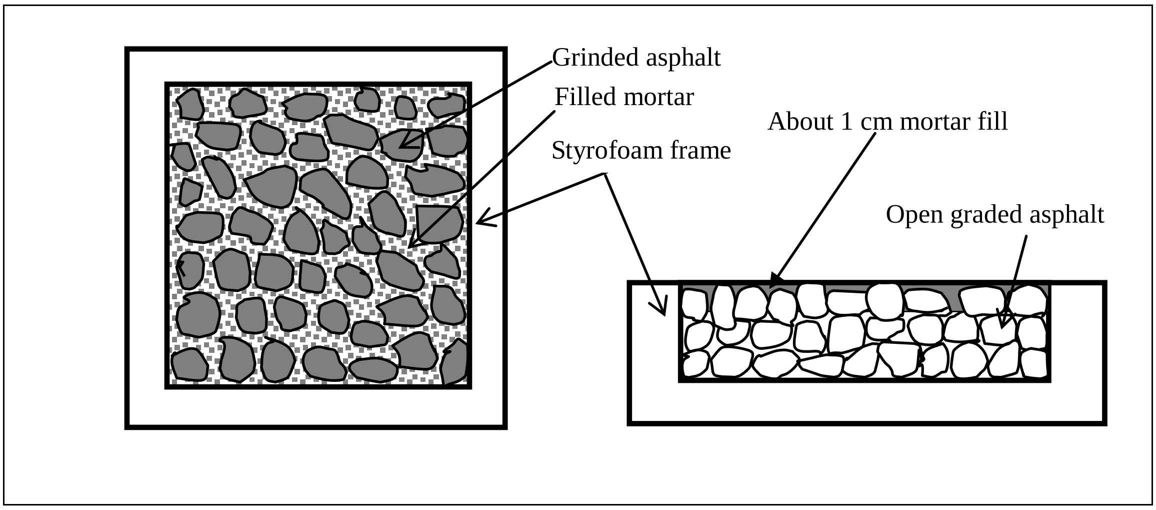
Mortar was prepared by experimental materials with design mix proportion (**Table 3.4**).

Table 3.4 Mix proportion of the prepared samples (For 12 samples)

Sample name	Cement (g)	Slag (g)	RS (g)	OS (g)	Water (g)	W/B	Cement type
OPC-RS	1,800	-	3,600	-	900	0.5	OPC
WPC-RS	1,800	-	3,600	-	900	0.5	WPC
OPC-Slag-RS	900	900	3,600	-	900	0.5	OPC
OPC-OS	1,000	-	-	2,000	1,100	1.1	OPC
HSPC-OS	1,000	-	-	2,000	1,100	1.1	HSPC
OPC-Slag-OS	250	750	-	2,000	1,150	1.15	OPC

Mortar preparing method and water binder ratio was same as the previous chapter. Binder aggregate ratio was 0.5 (1:2) in all cases. Cylindrical samples with 50 mm diameter and 100 mm height were prepared by mortar for compressive strength test in different curing condition.

The prepared mortar was filled on open graded asphalt concrete pavement block (30cm × 30cm × 5cm) by the help of vibrator (**Photo 3.3**) with about 1cm thickness (**Schematic view 3.1 & Photo 3.4**).



Schematic view 3.1 Schematic view of the mortar filled asphalt concrete

Pavement block surfaces were grinded after one week of insertion of the prepared mortar. After grinding pavement blocks were kept in normal room temperature about one month. These were used to test the surface heat reduction in controlled and open natural condition also the brightness test and the skid resistance test of the mortar filled pavement surface.

Photo 3.3 Mortar filling technique

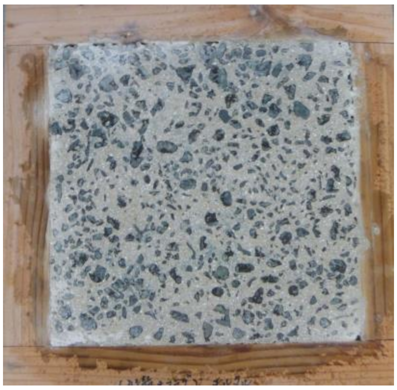


Photo 3.4 Mortar filled pavement

Another type (size and shape) of samples were prepared for brightness of the studied mortar pavement and spectrometric analysis test. The size of this type of samples was: length and width 40 mm and thickness 20 mm. At first 40 mm long mortar bar was prepared with each combination of the mix proportion and then cut with the required size by concrete cutter machine.

3.2.3 Test Procedure

(1) Compressive Strength Test

Three cylindrical samples were used for each age of curing. Samples produced from study aggregates were kept in 10℃, 20℃ and 30℃ constant room temperature for all the category just after to fill in the mould according to the experiment design and demoulded after three days, then, samples were cured in water at 10℃, 20℃ and 30℃ constant room temperature and in air at only 20℃ constant room temperature with relative humidity (R.H.) 50-60%, until the samples were used for compressive strength measurement at 3, 7, and 28 days. Compressive strength of each specimen was determined using universal testing machine with JIS A 1108 [**14**]. Loading rate and strength calculation method was same as previous chapter.

(2) Brightness Test

Brightness test was performed with Digital Color Reader (CR -13, Konica Minolta Optics Inc.) by the direction of the instrument manufacturer (**Photo 3.5**). Brightness was tested in twenty different points (**Photo 3.6**) on the every pavement block surface and their average value was calculated and used for the result discussion.

The $L^*a^*b^*$ color space (also referred to as CIELAB) is presently one of the most popular spaces for measuring object color and is widely used in virtually all fields. It is one of the uniform color spaces defined by CIE in 1976 in order to reduce one of the major problems of the original Yxy space: that equal distances on the x, y chromaticity diagram did not correspond to equal perceived color differences. In this space, L^*indicates lightness and a^* and b^* are the chromaticity coordinates **[28]**.

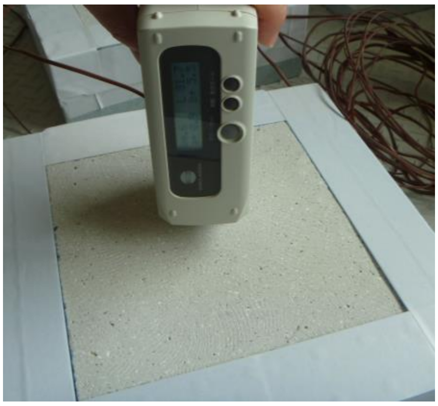


Photo 3.5 Brightness test with digital color reader

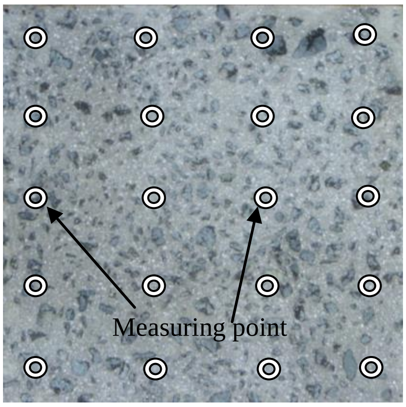
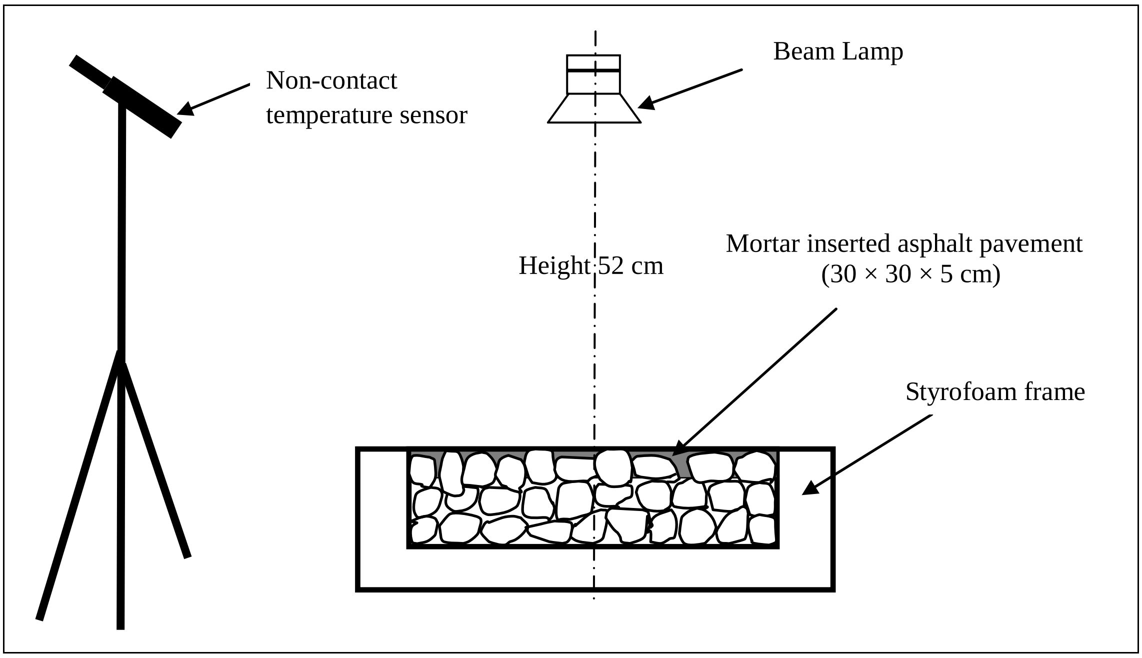


Photo 3.6 Measuring points distribution for brightness test

(3) Light Irradiation Test in controlled Condition

Light irradiation test was accomplished in two conditions: 1) inside the laboratory and environmentally controlled condition and 2) in open and natural weather condition.

To do this test different types of materials and instruments were used. Insulating frame was prepared by Styrofoam in the laboratory with the inside dimensions of 30 cm x 30 cm x 5 cm. Styrofoam was collected from the local market. This frame was used to set the prepared asphalt-mortar block for light irradiation test. A diffuser type beam lamp (110 Volt, 150 watt) was used to raise the temperature for this inside and controlled condition. The beam lamp was set at the height of 52 cm from the surface of the experimental block. A non-contact temperature sensor was used to determine the surface temperature of the experimental pavement block. Thermocouple was used to determine the room temperature and relative humidity of the environmentally controlled experimental room. An automatic data logging device (midi LOGGERGL 820) was used to receive and store the data from the used sensors. The data logger can receive and store 3 data in every minute. Data logger was started and stopped manually according to the experimental time distribution. An Environmentally-controlled room was used to perform the test. Specimen and the irradiation test equipment installed in the room (**Schematic view 3.2 & Photo 3.7**). The room temperature was tried to keep around 30 ± 1℃ and the relative humidity (RH) was tried to keep 50-60%



Schematic view 3.2 Schematic view of the light irradiation test in inside and controlled condition

For light irradiation test in inside controlled condition asphalt-mortar samples were stored for the test in the controlled room at 30℃ and with R.H. 50-60%. Every sample placed in styrofoam frame (30cm × 30cm × 5cm) and was kept in the light irradiation test room for 24 hours before the test for the purpose of temperature adjustment. The beam lamp irradiation was continued on the sample block for 3 hours. The data logger was received and stored data for total about 15 hours.

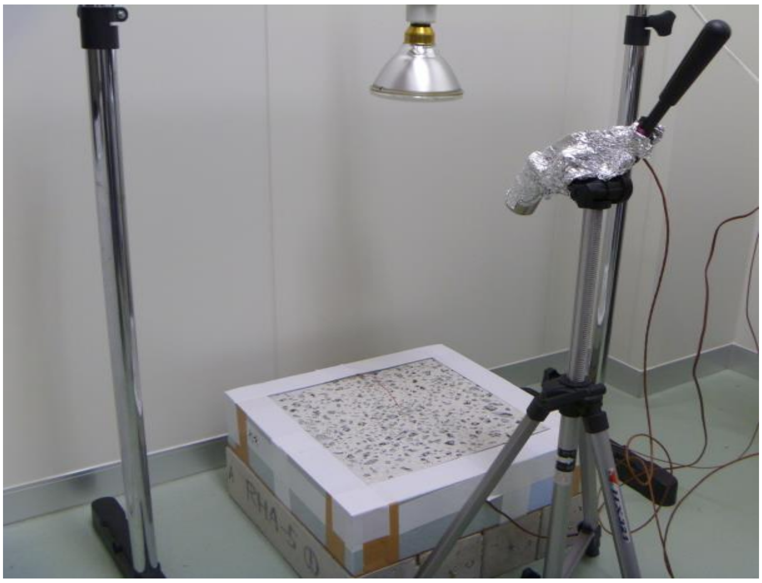


Photo 3.7 Photographic view of the light irradiation test in inside and controlled condition

(4) Light Irradiation Test in Open and Natural Condition

Light irradiation test in the open and natural condition was accomplished in three consecutive days at the end of the July, 2014. The test sample pavements were same as the samples used in the light irradiation test in the controlled room condition. The surface heat of the inside irradiation test was measured by a non-contact sensor and surface heat of the irradiation test in the open natural condition was measured by surface contact thermocouple. Temperature data were measured and recorded by digital data logger (**Photo 3.8**). Weather data were measured and recorded by “Watch Dog” weather station (**Photo 3.9**). The setting of the light irradiation test in open and natural condition is shown in **Photo 3.10**.

Photo 3.8 Data logger in outside irradiation test

Photo 3.9 Weather station for measuring weather data

Photo 3.10 Light irradiation test in open and natural condition

(5) Spectrometric Analysis

Six types of mortar (same mortar that was inserted on asphalt pavement) and asphalt concrete samples were prepared and used for the determination of the amount of solar irradiation reflection. Three samples of each type of mortar were used and their average was calculated for result discussion and to determine the mean albedo. Solar radiation reflection was determined by spectrometric analysis by the help of "MPC-3100" (**Photo 3.11**) and "UV-3100PC" (**Photo 3.12**). Wave length for this test was 380-2,600 nanometer (nm).

Photo 3.11 Sample inside the spectrometric radiation reflection measuring machine

Photo 3.12 Spectrometric radiation producer and reflection measuring machine

(6) Skid Resistance Test

The test was performed by using British Pendulum Tester. The experiment was accomplished by following the "**ASTM E 303:** Standard Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester". The skid resistance tester (British pendulum tester) was assembled and calibrated according to the Manufacturer`s manual. The sample block was set in front of the tester and under the pendulum head. The surface of the test block was wetted by water spray. The test room temperature was 20 ℃ and the test surface temperature was 20-22 ℃ that was measured by a non-contact temperature measuring device. By pressing the release knob, the pendulum head was released from initial horizontal position. The pendulum head stuck the test scale dial after sliding the wet test surface. The scale dial was indicated the skid resistance value for the test surface. The pendulum head was slide five times to take the resistance value from the test scale dial and their average value was calculated.

3.3. Results and Discussion

3.3.1 Strength of OPC-RS Mortar with No Slag Content

Compressive strength of RS mortar with OPC and no slag content in all ages was highest for 30℃ water curing and at 28 days (**Fig. 3.1**). This was about 6.5% more than 20℃ and 12% more than 10℃ water curing and lowest for 10℃ water curing. Strength for 20℃ water and air curing was almost same up to 7 days and finally at 28 days the lower strength recorded for air curing samples even than 10℃ water curing that was about 10.5% less than 20℃ and 5% less than 10℃ water curing.

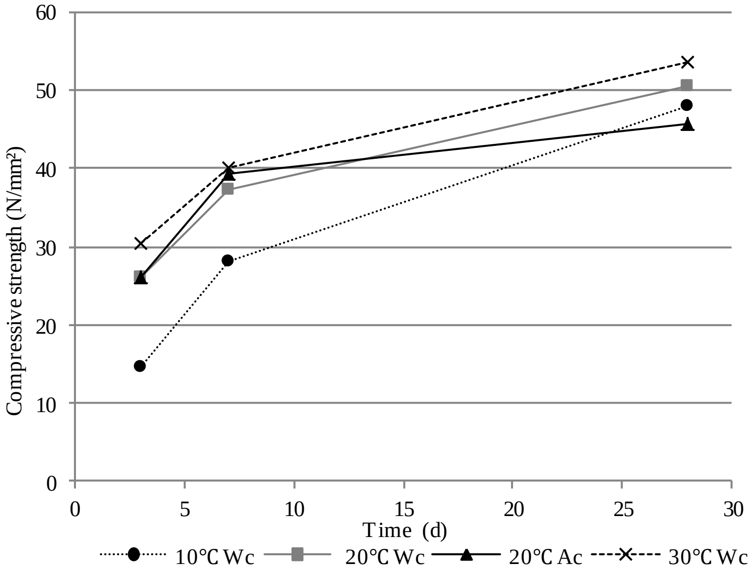


Fig. 3.1 Compressive strength of OPC-RS mortar with no slag content

At 28 days 30℃ water curing samples showed the highest compressive strength for RS mortar with OPC and no slag content and air curing in this case showed the lowest strength.

3.3.2 Strength of WPC-RS Mortar with No Slag Content

Compressive strength for RS mortar with WPC and no slag content (**Fig. 3.2**) up to 7 days was highest for 30℃ water curing and at 7 days this was 4% higher than 20℃ and 17% higher than 10℃ water curing and lowest for 10℃ water curing, finally at 28 days it was almost same for all cases except 20℃ air curing. At 28 days 20℃ air curing samples showed about 23% and 21% less strength than 20℃ and 10℃ water curing respectively.

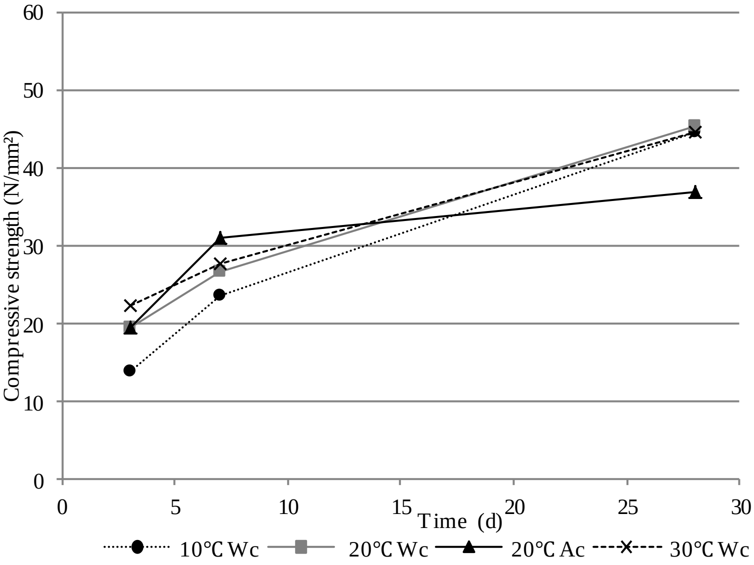


Fig. 3.2 Compressive strength of WPC-RS mortar with no slag content

For RS mortar with WPC and no slag content water curing at the temperature of 10℃ to 30℃ will give the different strength at initial age but same at 28 days. Air curing could give initial higher strength and at 28 days it might be lower.

3.3.3 Strength of OPC-RS Mortar with 50% Slag Content

Compressive strength of RS mortar with OPC and 50% slag content (**Fig. 3.3**) in all ages was highest for 30℃ water curing and at 28 days this was about 19% more than 20℃ and 66% more than 10℃ water curing and lowest for 10℃ water curing. Strength for 20℃ air curing was almost same or more than 20℃ water curing up to 7 days but at 28 days it was almost same as 10℃ and 40% less than 20℃ water curing.

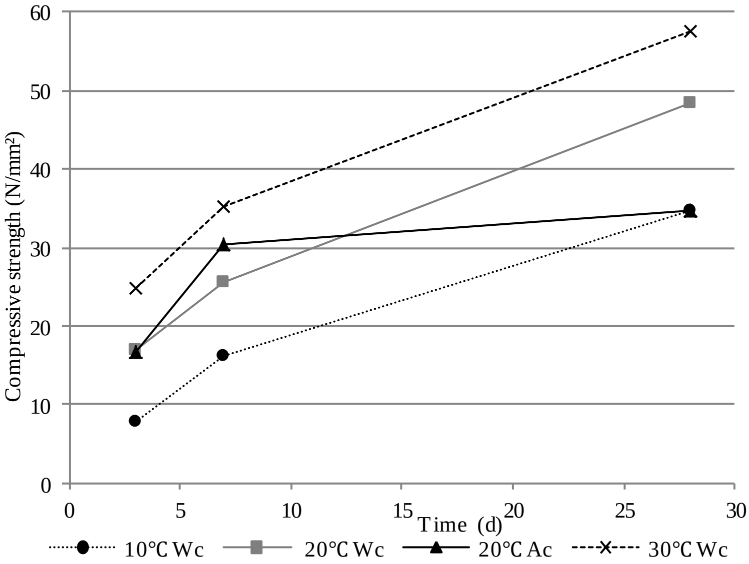


Fig. 3.3 Compressive strength of OPC-RS mortar with 50% slag content

3.3.4 Strength of OPC-OS with No Slag Content

Compressive strength of OS mortar with OPC and no slag content (**Fig. 3.4**) was highest at 20℃ and 30℃ water curing and lowest at 10℃ water curing condition and at middle age all of that were almost same except 10℃ water curing with lowering trend. Finally 20℃ and 10℃ water curing samples showed the highest and lowest strength respectively whereas 20℃ air and 30℃ water curing samples showed the same result.

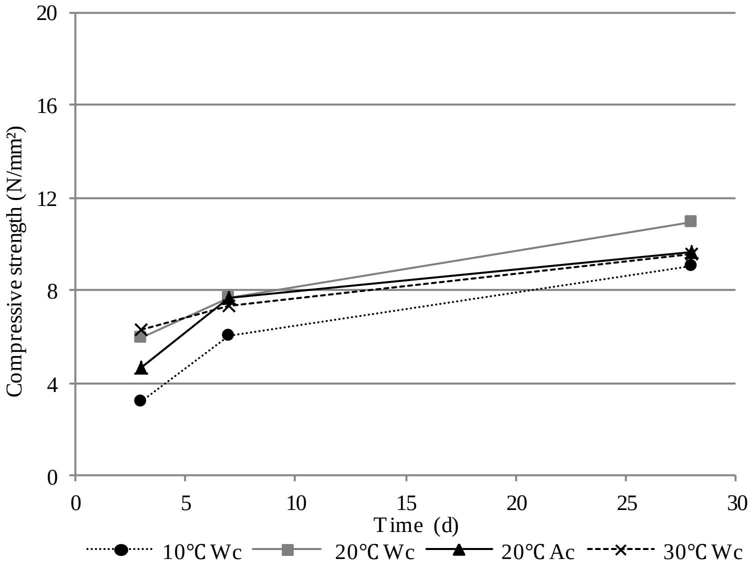


Fig. 3.4 Compressive strength of OPC-OS mortar with no slag content

20℃ water curing condition showed the highest strength for OPC-OS with no slag content samples and 20℃ air curing and 30℃ water curing samples showed no difference at 28 days.

3.3.5 Strength of HSPC-OS Mortar with No Slag Content

In case of OS mortar with HSPC and no slag content (**Fig. 3.5**) at early age 30℃ and 10℃ water curing showed the highest and lowest compressive strength respectively, 20℃ air and water curing samples showed the same result. At middle age 20℃ air curing samples showed the highest strength within the all samples and finally it was highest; 14% more than 30℃ and 31.5% more than 20℃ water curing and strength in all other condition was almost same.

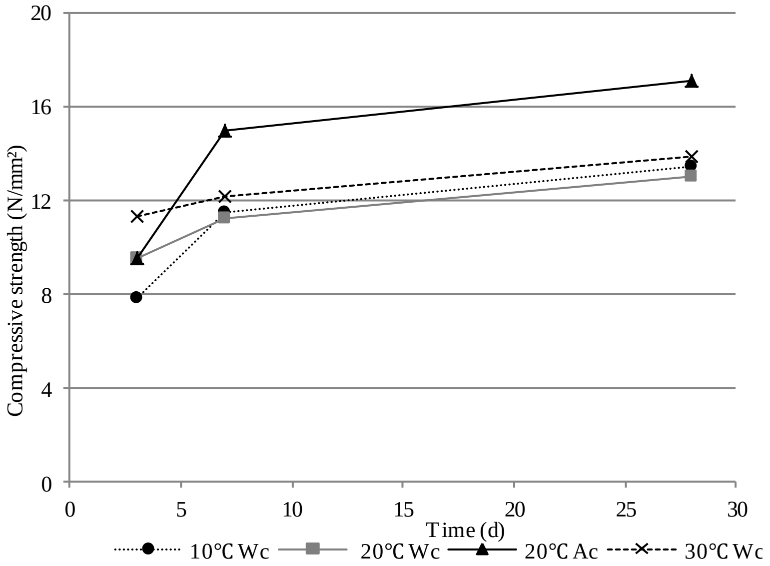


Fig. 3.5 Compressive strength of HSPC-OS mortar with no slag content

20℃ air curing showed highest strength for HSPC-OS mortar though it was lower at initial stage. Wet curing might be retarded the hardening of HSPC-OS mortar.

3.3.6 Strength of OPC-OS Mortar with 75% Slag

For OS mortar with OPC and 75% slag content (**Fig. 3.6**); 30℃ and 10℃ water curing sample showed the highest and lowest strength up to 7 days. At final age 20℃ water and air curing showed the highest and lowest strength whereas 10℃ and 30℃ water curing showed the same result.

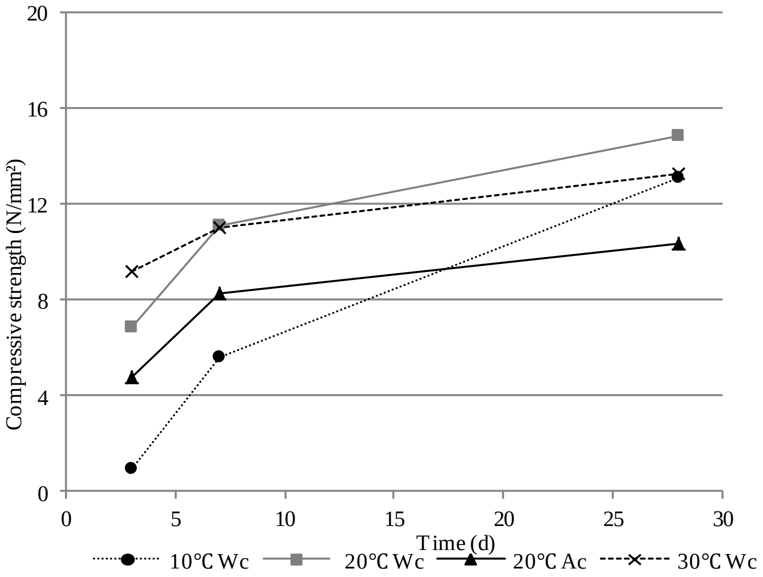


Fig. 3.6 Compressive strength of OPC-OS mortar with 75% slag content

Lower temperature curing condition could be suitable for long time strength development for OPC-OS mortar with 75% slag content. For the above compressive strength results of RS and OS mortar it was very much clear that higher curing temperature is preferable for the compressive strength due to the higher rate of hydration of cement and thus 30℃ curing temperature gave the higher compressive strength than 20℃ and 20℃ gave the higher compressive strength than 10℃ condition. Moisture curing is very important for strength development of mortar prepared with slag.

The hydration reaction rate increases with the increase in temperature and the density of hydration products at higher temperature is higher [**29**].

3.3.7 Brightness of the Sample Pavement Surfaces

The test value of the color tester were in three forms; a*, b* and L*. Where a* and b* was the color indicating parameter and L* was the brightness parameter. The values of a* b* were not considered for the result discussion, only the values of “L*” (brightness parameter) were considered for result discussions. Brightness of the study pavement surface was measured and expressed as numerical value; range with 0 (dark) to 100 (bright). The value indicates whether the surface was light or dark; larger the value indicates brighter the surface. Brightness was directly related with absorption and holding the heat of the sample. Brightest sample showed the lowest surface heat in this study.

Within the study pavement OS-Slag mortar sample showed the highest brightness and the asphalt with no mortar filling showed the lowest (**Fig. 3.7**). Within the RS mortar pavements; WPC-RS mortar showed the highest brightness and OPC-RS showed the lowest and within the OS mortar pavements; OPC-Slag-OS mortar showed the highest and OPC-OS mortar showed the lowest brightness.

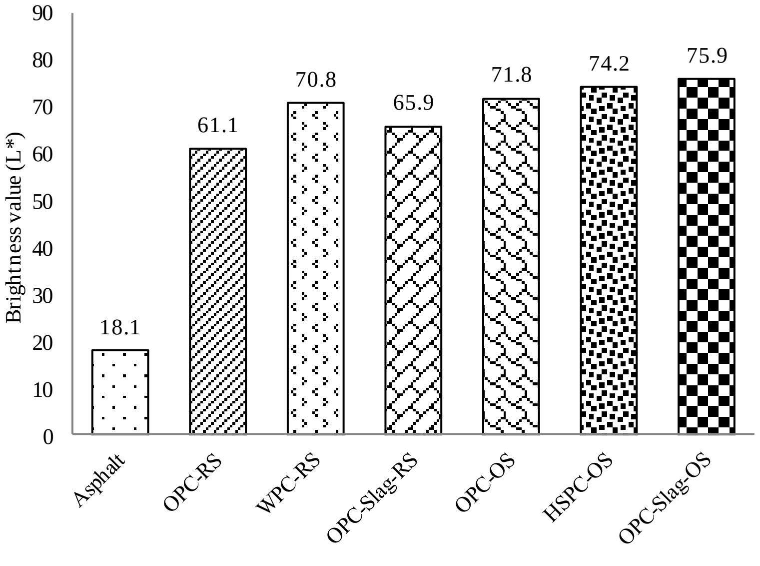


Fig. 3.7 Brightness of the mortar filled asphalt pavement surfaces

From the above discussion it could be said that heat will be absorbed and hold in pavements surface according to: OPC-Slag-OS < HSPC-OS < OPC-OS < WPC-RS < OPC- Slag-RS < OPC-RS < Asphalt.

3.3.8 Brightness of the Study Mortar Surface

Study mortar samples surface showed the same brightness behavior as mortar filled asphalt pavements surface (**Fig. 3.8**).

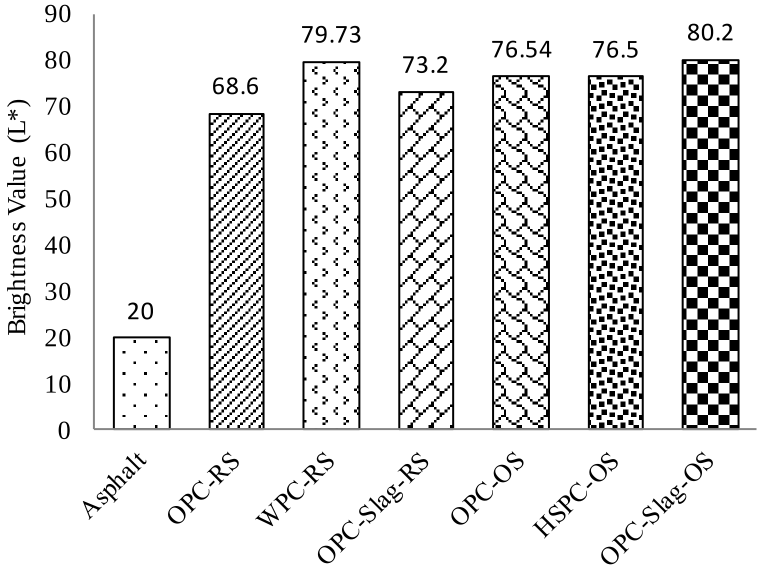


Fig. 3.8 Brightness of the study mortar surfaces

Though the brightness behavior was same, the brightness value was different for mortar and mortar filled pavement (**Fig. 3.9**) due to their application process. As the pavement surface contain the filled mortar as well as the asphalt, the brightness value of the mortar filled pavements were lower than the mortar surfaces brightness value.

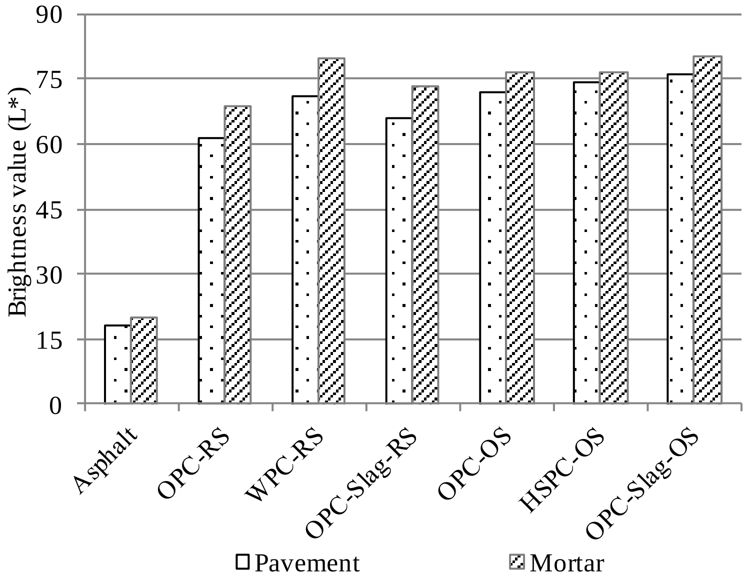


Fig. 3.9 Brightness of mortar and mortar fill pavement

3.3.9 Effect of Light Irradiation on Pavement Surface Temperature in Inside and Controlled Condition

Asphalt pavement with top filling by OPC-RS mortar reduced the surface heat by 9.3℃, WPC-RS mortar reduced by 13.3℃, OPC-Slag-RS mortar reduced 11.5℃, OPC-OS mortar reduced 14.2℃, HSPC-OS mortar reduced 14.8℃ and OPC-Slag-OS mortar reduced 16.1℃ in compare with asphalt concrete pavement with no top filling (**Fig. 3.10**).

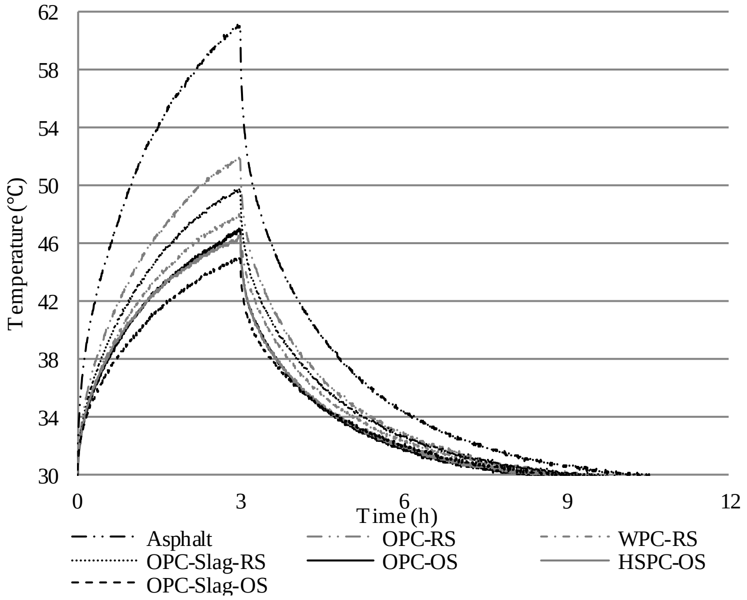


Fig. 3.10 Surface temperature in inside and controlled condition

It indicates that heat was absorbed and holds in pavement surfaces according to: "OPC-Slag-OS < HSPC-OS < OPC-OS < WPC-RS < OPC-Slag-RS < OPC-RS < Asphalt", that supports the brightness test results. This was due to the variation of brightness and absorption of heat by the pavement surfaces.

Heat reflecting pavements reduced their surface temperature due to the increasing in reflectance of solar radiation on the pavement surface [**22**]. Heat effects are caused by the heat absorption and reflectance with surfaces [**30**].

3.3.10 Effect of Light Irradiation on Pavement Bottom Temperature in Inside and Controlled Condition

Asphalt pavement with top filling by OPC-RS mortar reduced 6℃ bottom heat, WPC-RS mortar reduced 9.2℃, OPC-Slag-RS mortar reduced 8℃, OPC-OS mortar reduced 10.3℃, HSPC-OS mortar reduced 11.2℃ and OPC-Slag-OS mortar reduced 12.8℃ in compare with asphalt concrete pavement with no top filling (**Fig. 3.11**).

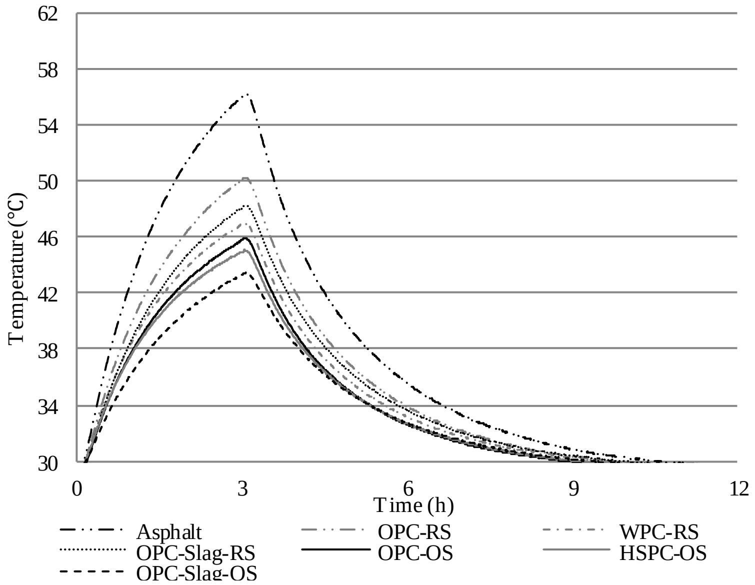


Fig. 3.11 Bottom temperature in inside and controlled condition

According to the light irradiation test result heat was absorbed and holds in pavement samples bottom according to: “OPC-Slag-OS < HSPC-OS < OPC-OS < WPC-RS < OPC-Slag-RS < OPC-RS < Asphalt” which supports completely the brightness test results and proved the consistency of the both test results.

3.3.11 Effect of Light Irradiation on Pavement Surface Temperature in Open and Natural Weather Condition

Heat developed in experimental pavement surfaces and weather data were measured in the open natural condition in three consecutive days but the data for result discussion was taken (for all samples) at the time when the asphalt pavement reached at highest temperature within one day time period (**Fig. 3.12**).

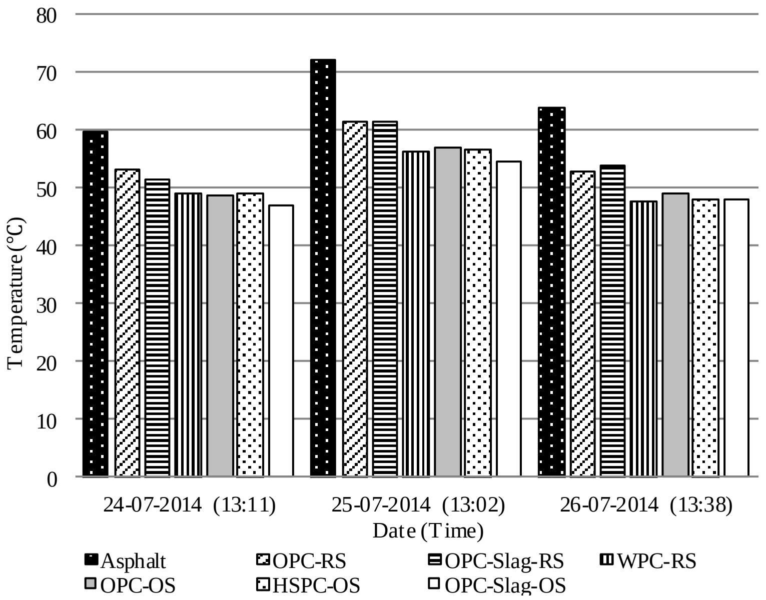


Fig. 3.12 Maximum surface temperature in open and natural condition

The highest and lowest temperature showed asphalt pavement and asphalt with OPC-Slag-OS mortar top filling pavement respectively and other samples also showed almost same trend of temperature development in all the three consecutive days as like as the irradiation test in the controlled room condition. The OPC-Slag-OS mortar pavements reduced the surface heat almost 13℃, 17.7℃ and 15.8℃ in compare with the asphalt pavement surface in the three consecutive days. Within the three consecutive days, the last two days heat reduction rate were almost same but the first day it was quite lower in compare with the last two days due to the frequent rise and fall of the solar radiation (**Fig. 3.13**).

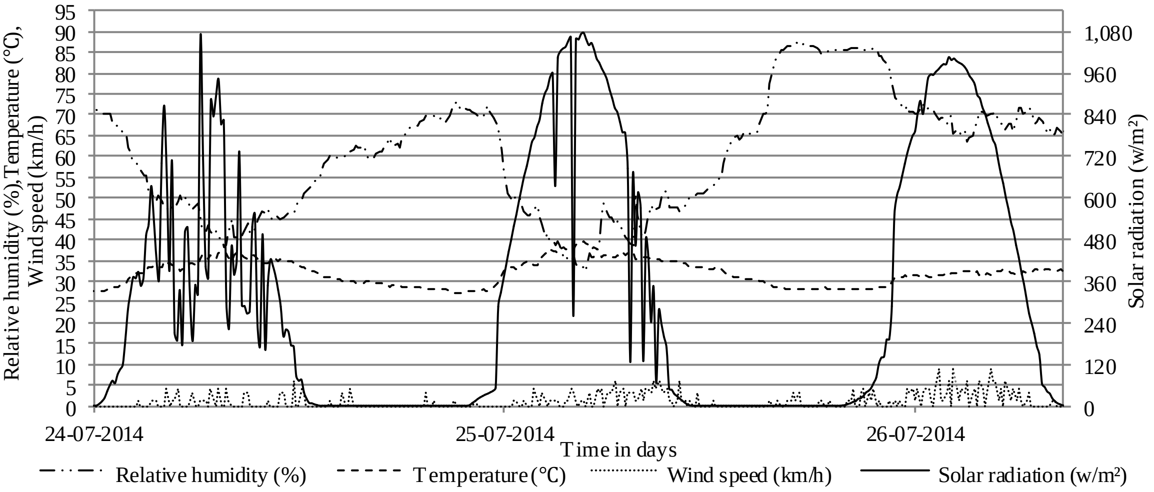


Fig. 3.13 Solar radiation, relative humidity, air temperature and wind speed of the experimental period

3.3.12 Spectrometric Analysis for Asphalt and Filling Mortar

Within the tested samples OPC-Slag-OS mortar was reflected maximum amount (72.3%) of solar radiation and asphalt concrete was reflected only 9.1%, which was the lowest amount. The maximum amount of solar radiation reflection was 72.3% by OPC-Slag-OS, 69.6% by HSPC-OS, 67.4% by OPC-OS, 63.1% by WPC-RS, 51.8% by OPC-Slag-RS, 48.6% by OPC-RS and 9.1% by asphalt pavement surface (**Fig. 3.14**). It indicates that asphalt pavement will absorb maximum and OPC-Slag-OS will absorb minimum solar radiation and the others accordingly. According to this test results heat will be absorbed and hold in sample surfaces: OPC-Slag-OS < HSPC-OS < OPC-OS < WPC-RS < OPC-Slag-RS < OPC-RS < Asphalt.

The sample which reflects the more amounts (%) of solar radiation is good for surface heat reduction and vice versa. For example, white surface is cooler than black surface because white surface reflects the maximum amount (%) of solar radiation (almost 100%). On the other hand, black surface is hotter than white surface because black surface reflects the minimum amount (%) of solar radiation (almost 0%). So, from the study result we can say that asphalt surface is the hottest and slag blended oyster shell mortar surface is the coolest surface within the study mortar samples.

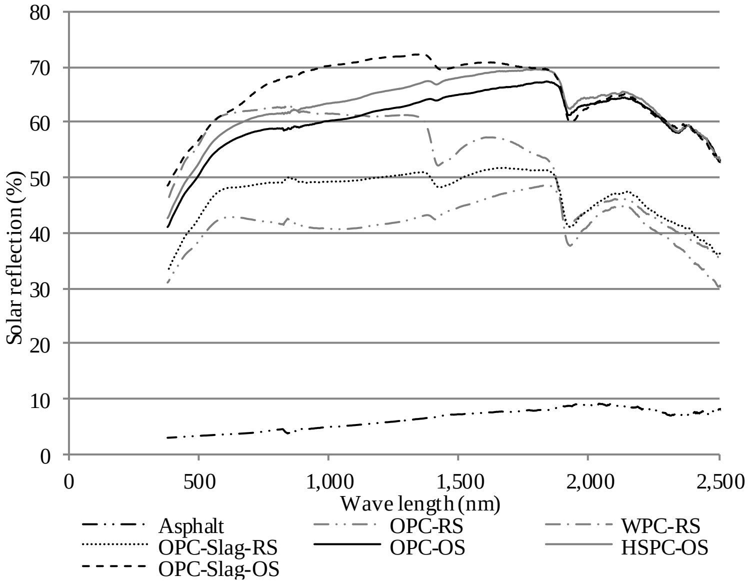


Fig. 3.14 Amount of solar radiation reflection of the experimental mortar samples and asphalt concrete

The concrete mix with 70% slag as cement replacement achieves the albedo of 0.582 [**31**]. In this study the albedo was 0.466 for OPC-Slag-RS samples due to the mix with 50% cement replacement with slag and for OPC-Slag-OS samples albedo was 0.651 due to the 75% cement replacement with slag and the use of OS as aggregate.

3.3.13 Skid Resistance Test Result in Wet Condition

OPC-Slag-RS mortar inserted pavement showed the highest and OPC-RS inserted pavement showed the lowest skid resistance within the RS mortar inserted pavements (**Fig. 3.15**). Skid resistance can be increased 7% by using slag in RS mortar. OPC-OS mortar inserted pavement showed the highest and HSPC-OS inserted pavement showed the lowest skid resistance within the OS mortar inserted pavements. OPC-Slag-OS mortar inserted pavement showed 0.6% increased skid resistance than HSPC-OS inserted pavement.

The high value of the skid resistance indicates the high skid resistance and low skidding risk. Low value indicates the risk of skidding. The surface with the BPN value more than or equal 45 could be used in walkways, parking area and other suitable sites [**32**]. So, from the test result we can say that asphalt pavement surface have the highest skid resistance property and the other samples also can be used in designated places.

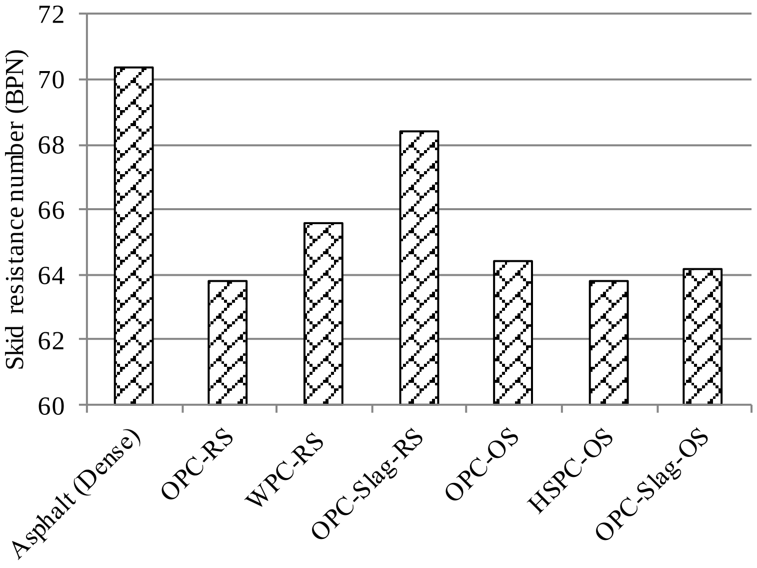


Fig. 3.15 Skid resistance test values of the study pavement surface in wet condition

3.3.14 Density of the Mortar Samples

Density of the studied mortar sample was measured at every compressive strength test date and the result is shown in **Table 3.5**.

Table 3.5 Density (kg/m^3) of the mortar samples at different age

Sample	3 Days	7 Days	28 Days
OPC RS (10℃ Wc)	2,205	2,221	2,231
OPC RS (20℃ Wc)	2,217	2,234	2,233
OPC RS (20℃ Ac)	2,217	2,135	2,117
OPC RS (30℃ Wc)	2,210	2,230	2,234
WPC RS (10℃ Wc)	2,196	2,204	2,210
WPC RS (20℃ Wc)	2,172	2,192	2,208
WPC RS (20℃ Ac)	2,172	2,107	2,082
WPC RS (30℃ Wc)	2,139	2,189	2,201
OPC 50%S-40 RS (10℃ Wc)	2,158	2,187	2,200
OPC 50%S-40 RS (20℃ Wc)	2,182	2,193	2,216
OPC 50%S-40 RS (20℃ Ac)	2,171	2,094	2,066
OPC 50%S-40 RS (30℃ Wc)	2,164	2,193	2,209
OPC OS (10℃ Wc)	1,623	1,669	1,695
OPC OS (20℃ Wc)	1,696	1,735	1,736
OPC OS (20℃ Ac)	1,642	1,440	1,350
OPC OS (30℃ Wc)	1,615	1,658	1,675
HSPC OS (10℃ Wc)	1,664	1,710	1,719
HSPC OS (20℃ Wc)	1,705	1,757	1,751
HSPC OS (20℃ Ac)	1,705	1,549	1,459
HSPC OS (30℃ Wc)	1,615	1,688	1,712
OPC 75%S-40 OS (10℃ Wc)	1,645	1,686	1,699
OPC 75%S-40 OS (20℃ Wc)	1,709	1,738	1,730
OPC 75%S-40 OS (20℃ Ac)	1,682	1,533	1,420
OPC 75%S-40 OS (30℃ Wc)	1,623	1,649	1,666

3.4 Conclusions

1) At 28 days highest compressive strength of RS mortar samples showed in 30℃ curing whereas OS mortar samples showed in 20℃ curing condition.
2) For WPC-RS mortar water curing at the temperature of 10℃ to 30℃ showed the different strength at initial age but same at 28 days.
3) For HSPC-OS mortar air curing would be better for higher compressive strength.
4) OPC-Slag-OS mortar was the brightest sample that showed highest albedo in spectrometric analysis test.
5) OPC-Slag-OS mortar filled pavement reduced 16.1℃ surface temperature in controlled and 13-17.7℃ surface temperature in open and natural light irradiation test in compare with asphalt pavement.
6) Slag blended oyster shell aggregate mortar filled asphalt pavement could be used in walkways, parking area and other suitable sites.

Chapter 4

Conclusions and Future Research

4.1 Conclusions

The following conclusions can be drawn for the strength properties of the ground granulated blast furnace slag and oyster shell blended mortar:

1) Binder aggregate ratio has an effect on the compressive strength. The higher difference between the binder and aggregate mixing amount will lower the compressive strength. In this study, binder aggregate ratio was used 1:2 and 1:3. The compressive strength of study samples was higher for all the design combinations with binder aggregate ratio 1:2 in compare with binder aggregate ratio 1:3.
2) The strength of slag blended mortar increased with the age of the sample. Compressive strength at 91 days was higher than 28 days strength, compressive strength at 28 days was higher than 7 days strength and compressive strength at 7 days was higher than 3 days strength. Cement could be partially replaced up to 85% by ground granulated blast furnace slag and 75% slag blended oyster shell mortar sample will give the highest compressive strength in compare with zero slag used oyster shell mortar sample..
3) Slag blended river sand mortar have lower early strength but in later age it was higher in compare with no slag used river sand mortar samples. At early age 50% slag used samples compressive strength was 34% lower than zero slag used samples`. At final age slag used samples compressive strength was 16% higher than zero slag used samples.
4) To get higher compressive strength in compare with zero slag mortar, cement

could be replaced by the granulated blast furnace slag up to 50% in river sand mortar. At final age compressive strength of 75% slag used samples was 17% lower and the strength of 50% slag used samples was 16% higher than that of the zero slag used samples.

5) To get higher compressive strength, Portland cement could be replaced by high early strength Portland cement (HSPC) in oyster shell mortar. In this case, the binder aggregate mixing ratio 1:3 will reduce the compressive strength in compare with ordinary Portland cement and the binder aggregate mixing ratio 1:2 will increase the compressive strength in compare with ordinary Portland cement.
6) The replacement of river sand by the oyster shell aggregate reduced the compressive strength of the mortar samples about 70%. The strength of oyster shell aggregate mortar can be increased up to 42% than zero slag used oyster shell mortar by using slag as replacement of cement. In considering the maximum and minimum Strength reduction for aggregate replacement (river sand replaced by slag) could be minimized up to 20% by using slag in oyster shell mortar.
7) Super plasticizer (SP) increased the compressive strength of the zero slag and slag blended oyster shell mortar. The compressive strength of super plasticizer used oyster shell aggregate mortar with and without slag content increased 43% and 40% respectively due to the decrease of water-binder ratio. The water-binder ratio decreased about 23% by the use of SP.
8) Fineness of the slag has an effect on the strength properties of mortar. Finer particles containing slag showed the higher compressive strength. Compressive strength of the oyster shell mortar samples prepared with slag-80 (specific

surface area 8000 cm^2/g) was 4% higher than the mortar samples prepared with slag-60 (specific surface area 6000 cm^2/g) and the strength of the oyster shell mortar samples prepared with slag-60 (specific surface area 6000 cm^2/g) was 4% higher than the mortar samples prepared with slag-40 (specific surface area 4000 cm^2/g).

The followings can be concluded for the strength properties of the slag blended mortar samples in different curing conditions and their use in pavement construction-

1) River sand mortar samples showed their highest compressive strength in 30℃ water curing condition. The compressive strength of river sand mortar (without using slag) samples in 30℃ water curing was about 6.5% more than 20℃ and 12% more than 10℃ water curing and was lowest for 10℃ water curing. The compressive strength of river sand mortar (with 50% slag blended) samples in 30℃ water curing was about 19% more than 20℃ and 66% more than 10℃ water curing also was lowest for 10℃ water curing.
2) Oyster shell mortar samples showed their highest compressive strength in 20℃ water curing condition. Compressive strength of oyster shell aggregate mortar (without using slag) was highest in 20℃ and lowest in 10℃ water curing whereas 20℃ air and 30℃ water curing samples showed the same result. Compressive strength of oyster shell aggregate mortar (75% slag blended) was highest in 20℃ water and lowest in 20℃ air curing whereas 10℃ and 30℃ water curing showed the same result.
3) Curing temperature have effect on early strength of river sand mortar prepared with white Portland cement (WPC) but in later age it was almost same in all the conditions. 20℃ air curing showed initial higher strength but at 28 days it was

lowered. At 28 days 20℃ air curing samples showed about 23% and 21% less strength than 20℃ and 10℃ water curing respectively.

4) Air curing showed the higher compressive strength for oyster shell mortar prepared with high early strength cement. Compressive strength of oyster shell mortar prepared with high early strength cement in 20℃ air curing was 14% higher than 30℃ and 31.5% higher than 20℃ water.
5) In spectrometric analysis test, slag blended oyster shell (OS) mortar was the brightest sample also showed the highest albedo and asphalt concrete pavement was the darkest sample also showed the lowest albedo. Within the river sand mortar pavements surface; white Portland cement mortar showed the highest brightness and ordinary Portland cement showed the lowest brightness. Within the OS mortar pavements surface; slag blended oyster shell mortar showed the highest and zero slag used oyster shell mortar showed the lowest brightness.
6) Slag blended oyster shell mortar filled pavement showed the lowest surface temperature and asphalt pavement showed the highest surface temperature in controlled as well as in open and natural light irradiation test. Slag blended oyster shell mortar filled pavement reduced 16.1℃ surface temperature in controlled and 13℃ to 17.7℃ surface temperature in open and natural light irradiation test in compare with asphalt pavement.
7) Slag blended oyster shell aggregate mortar filled asphalt pavement could be used in walkways, parking area and other suitable sites.

4.2 Future Research:

The research works mentioned in this thesis was focused on the strength properties of the ground granulated blast furnace slag blended oyster shell aggregate mortar and their usability in pavement construction as eco-mortar.

The strength development mechanism in ground granulated blast furnace slag used mortar and concrete has already been determined by the relevant researchers`, but the strength development mechanism in oyster shell aggregate used mortar or slag blended oyster shell aggregate mortar is still unknown. Beside these density development pattern of the study samples with different percentage of slag content and with different binder aggregate mixing ratio is also unknown. Future researchers` have the opportunity to conduct research work on the mentioned issues.

In future, research could be conducted to investigate the feasibility of the uses of mentioned eco-mortar in other fields of construction. For example, it could be possible to use the eco-mortar to prepare the cool tiles, cool walls etc.

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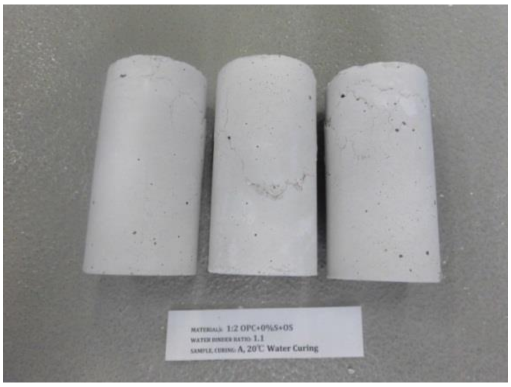
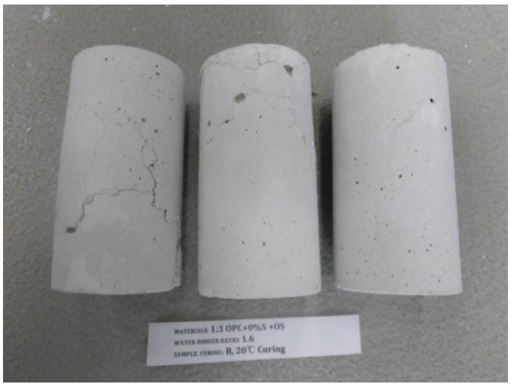
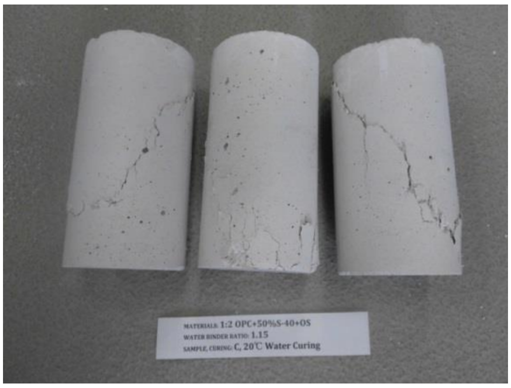
Appendix



Materials: 1:2 OPC+0%S+OS
Curing: 20°C Water Curing



Materials: 1:3 OPC+0%S +OS
Curing: 20°C Curing



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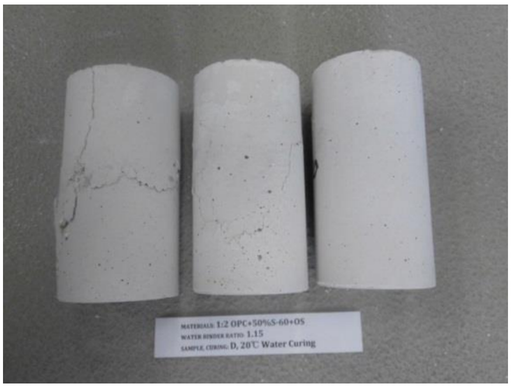
Curing: 20°C Water Curing



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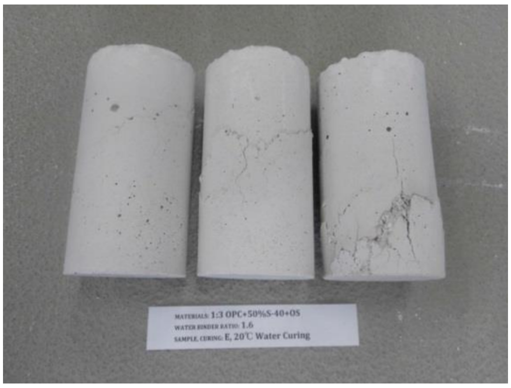
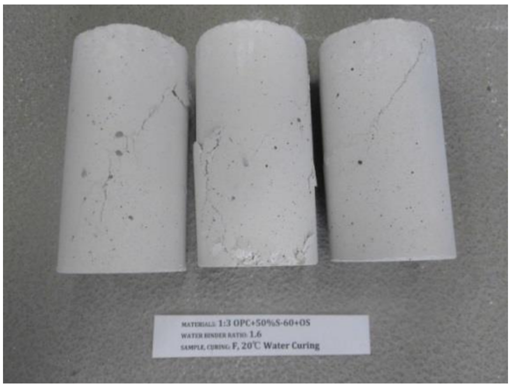
Curing: 20°C Water Curing

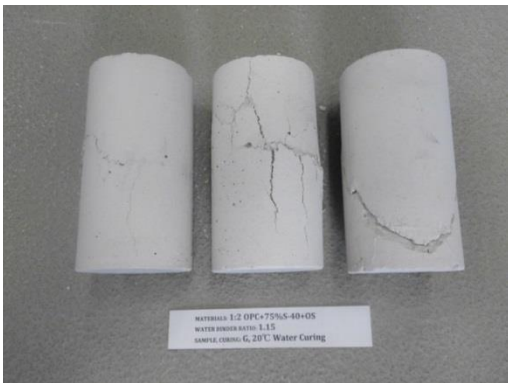


Materials: 1:3 OPC+50%S-40+OS
Curing: 20°C Water Curing



Materials: 1:3 OPC+50%S-60+OS
Curing: 20°C Water Curing

Photo A1 Crushed samples after compressive strength test those prepared with different combinations of ground granulated blast furnace slag and oyster shell aggregate.



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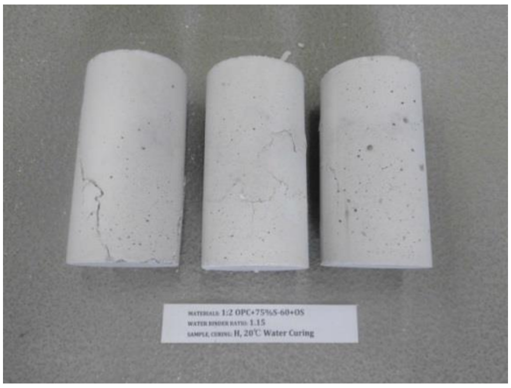
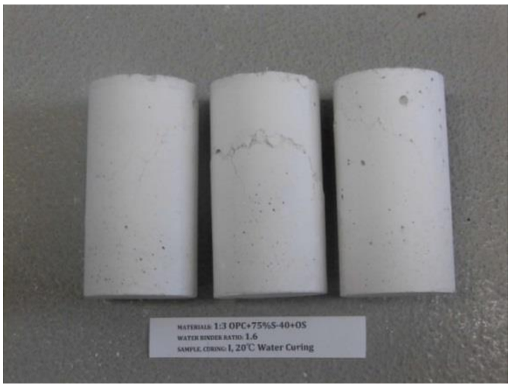
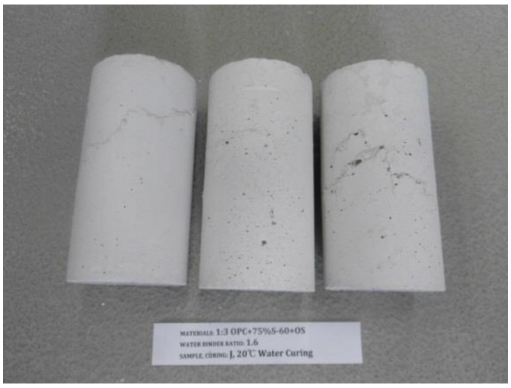
Curing: 20°C Water Curing



Materials: 1:2 OPC+75%S-60+OS
Curing: 20°C Water Curing

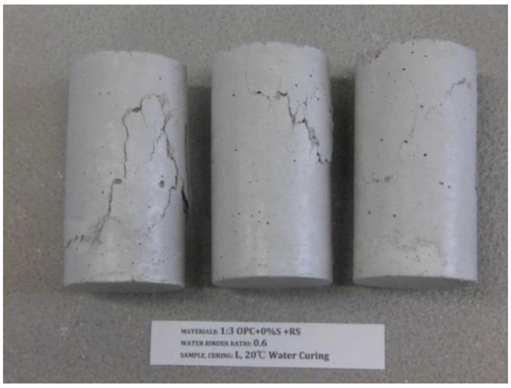


Materials: 1:3 OPC+75%S-40+OS
Curing: 20°C Water Curing



Materials: 1:3 OPC+75%S-60+OS
Curing: 20°C Water Curing

Materials: 1:2 OPC+0%S +RS
Curing: 20°C Water Curing



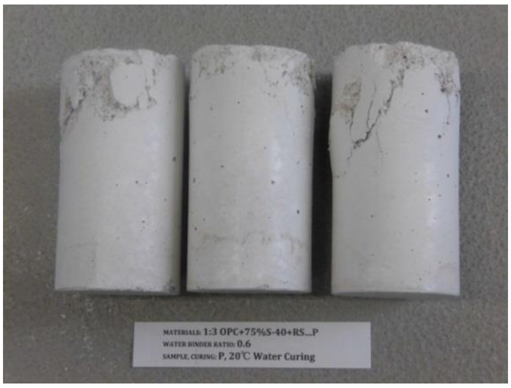
Materials: 1:3 OPC+0%S +RS
Curing: 20°C Water Curing

Photo A2 Crushed samples after compressive strength test those prepared with different combinations of ground granulated blast furnace slag and oyster shell aggregate.

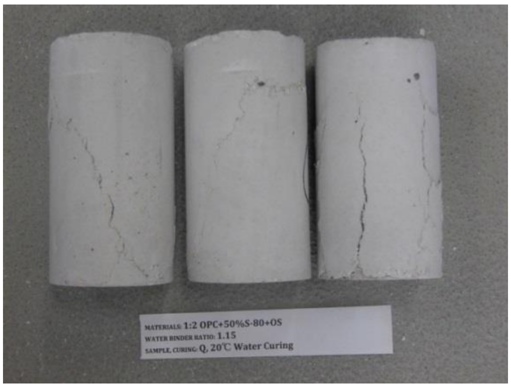
Materials: 1:2 OPC+50%S-40+RS
Curing: 20℃ Water Curing

Materials: 1:3 OPC+50%S-40+RS
Curing: 20℃ Water Curing

Materials: 1:2 OPC+75%S-40+RS
Curing: 20℃ Water Curing



Materials: 1:3 OPC+75%S-40+RS…P
Curing: 20℃ Water Curing



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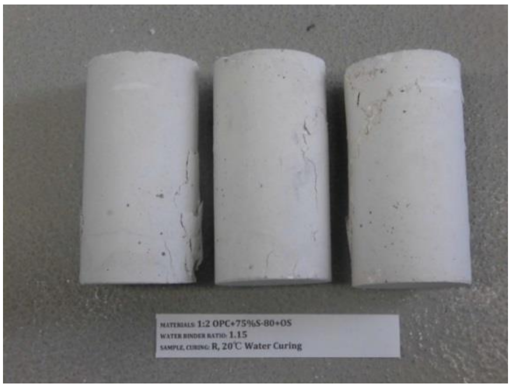
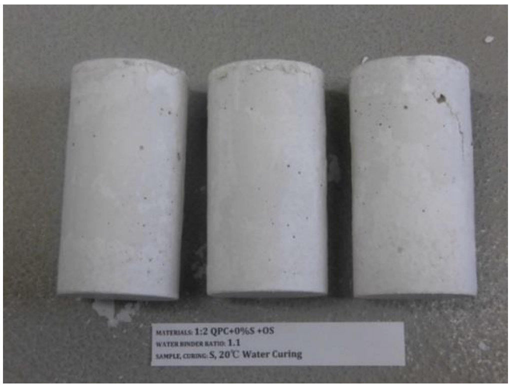
Curing: 20℃ Water Curing

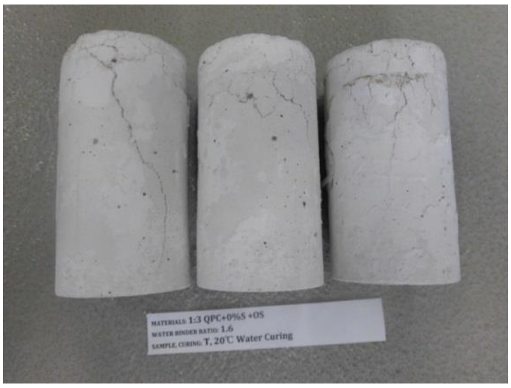


Materials: 1:2 OPC+75%S-80+OS
Curing: 20℃ Water Curing

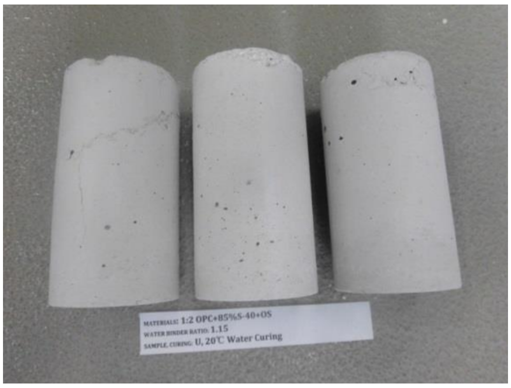
Photo A3 Crushed samples after compressive strength test those prepared with different combinations of ground granulated blast furnace slag and oyster shell aggregate.



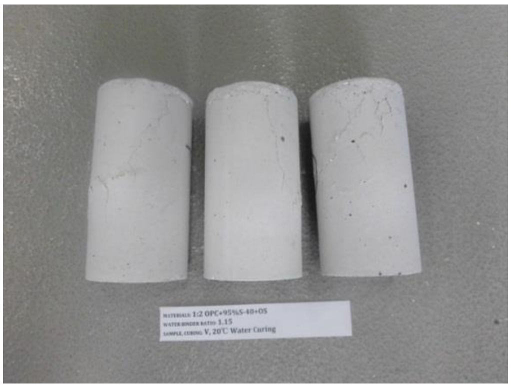
Materials: 1:2 QPC+0%S +OS
Curing: 20°C Water Curing



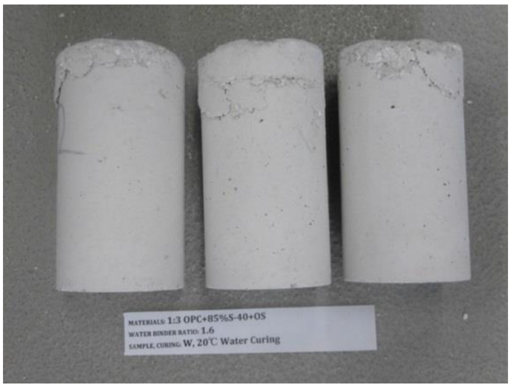
Materials: 1:3 QPC+0%S +OS
Curing: 20°C Water Curing



Materials: 1:2 OPC+85%S-40+OS
Curing: 20°C Water Curing



Materials: 1:2 OPC+95%S-40+OS
Curing: 20°C Water Curing



Materials: 1:3 OPC+85%S-40+OS
Curing: 20°C Water Curing

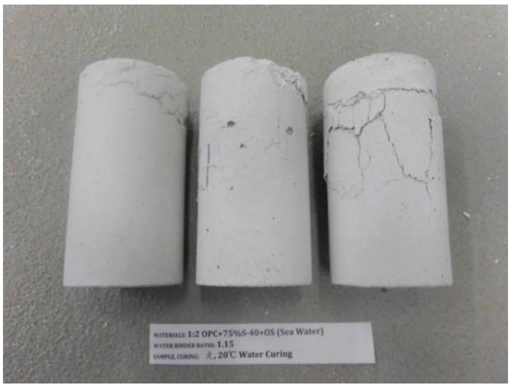
Materials: 1:3 OPC+95%S-40+OS..X
Curing: 20°C Water Curing

Photo A4 Crushed samples after compressive strength test those prepared with different combinations of ground granulated blast furnace slag and oyster shell aggregate.

Materials: 1:2 OPC+0%S +OS (Tape Water)
Curing: 20°C Water Curing

Materials: 1:2 OPC+75%S-40+OS (Tape Water)
Curing: 20°C Water Curing

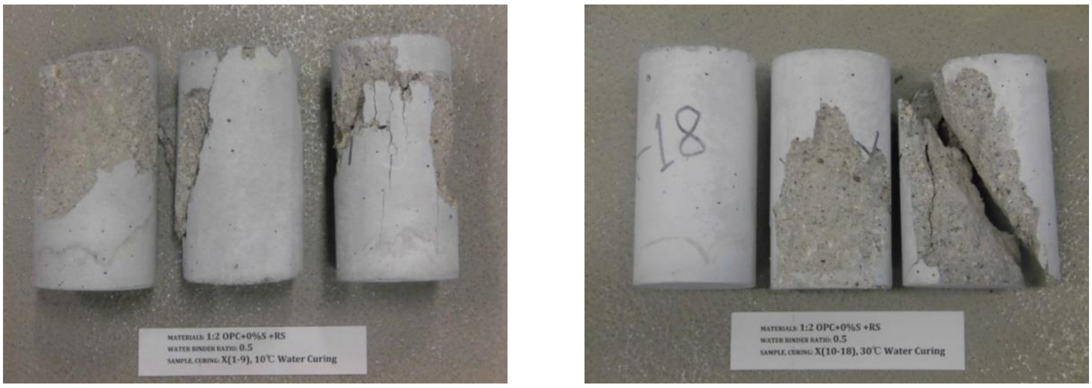
Materials: 1:2 OPC+0%S +OS (Sea Water)
Curing: 20°C Water Curing



Materials: 1:2 OPC+75%S-40+OS (Sea Water)
Curing: 20°C Water Curing

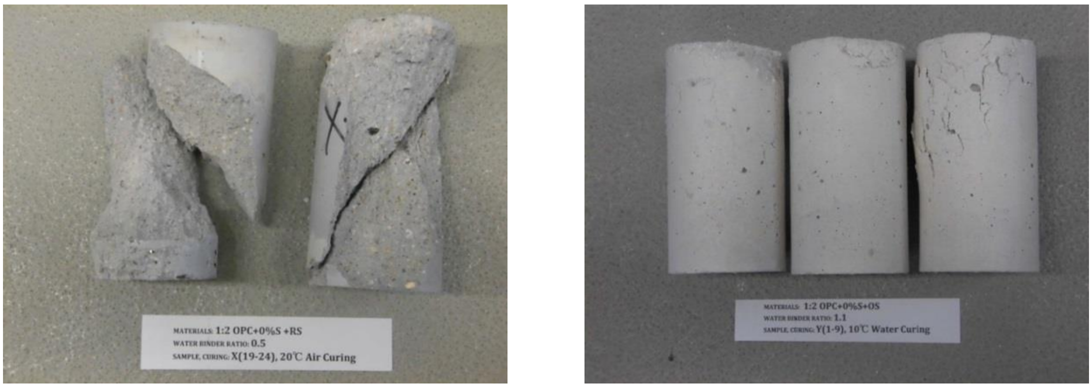
Materials: 1:2 OPC+0%S +OS (Tape Water)
Curing: 20°C Air Curing

Photo A5 Crushed samples after compressive strength test those prepared with different combinations of ground granulated blast furnace slag and oyster shell aggregate.



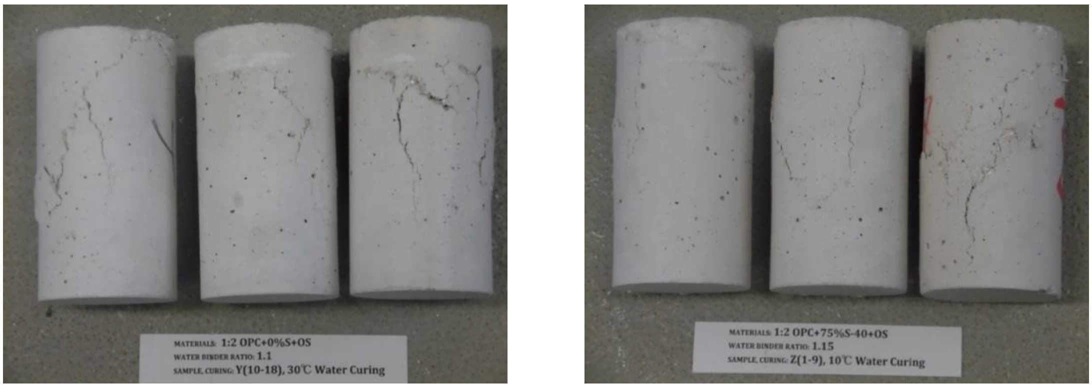
Materials: 1:2 OPC+0%S +RS
Curing: 10℃ Water Curing

Materials: 1:2 OPC+0%S +RS
Curing: 30℃ Water Curing



Materials: 1:2 OPC+0%S +RS
Curing: 20℃ Air Curing

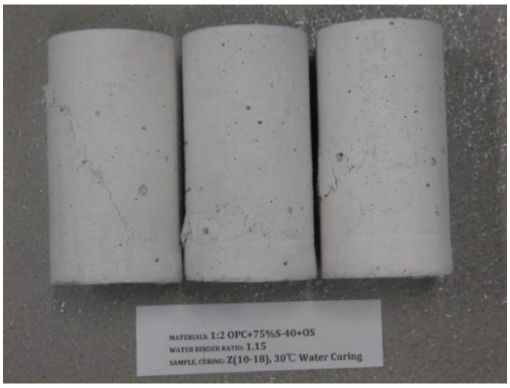
Materials: 1:2 OPC+0%S+OS
Curing: 10℃ Water Curing



Materials: 1:2 OPC+0%S+OS
Curing: 30℃ Water Curing

Materials: 1:2 OPC+75%S-40+OS
Curing: 10℃ Water Curing

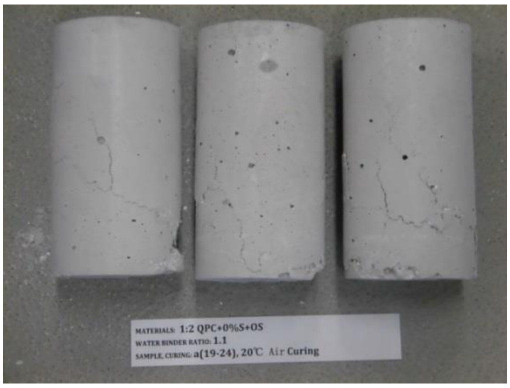
Photo B1 Crushed samples after compressive strength test those cured in different Curing conditions and prepared with different combinations of ground granulated blast furnace slag and oyster shell aggregate.



Materials: 1:2 OPC+75%S-40+OS
Curing: 30°C Water Curing

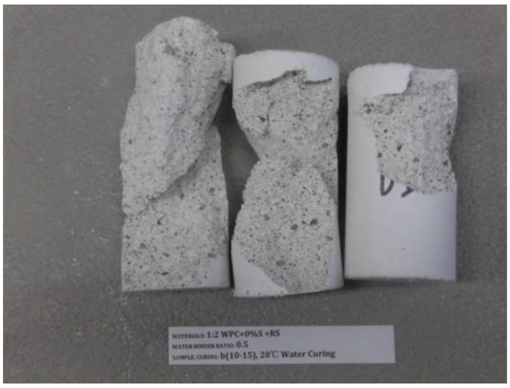
Materials: 1:2 QPC+0%S+OS
Curing: 10°C Water Curing

Materials: 1:2 QPC+0%S+OS
Curing: 30°C Water Curing



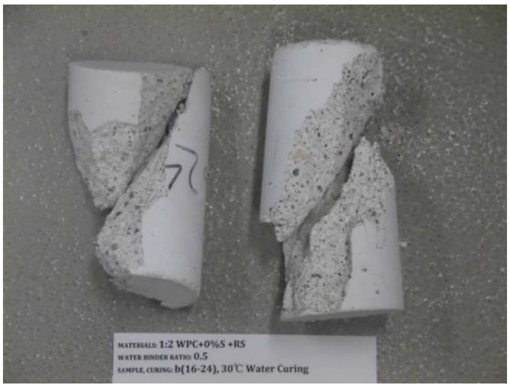
Materials: 1:2 QPC+0%S+OS
Curing: 20°C Air Curing

Materials: 1:2 WPC+0%S +RS
Curing: 20°C Air Curing



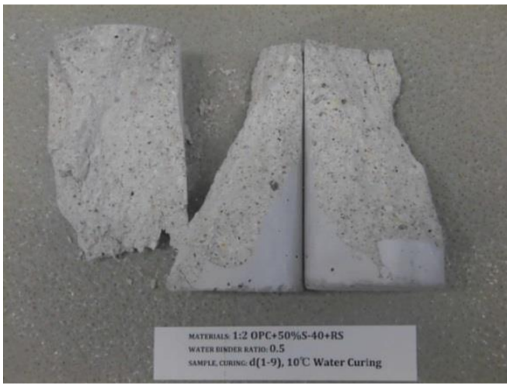
Materials: 1:2 WPC+0%S +RS
Curing: 20°C Water Curing

Photo B2 Crushed samples after compressive strength test those cured in different Curing conditions and prepared with different combinations of ground granulated blast furnace slag and oyster shell aggregate.



Materials: 1:2 WPC+0%S +RS
Curing: 30°C Water Curing

Materials: 1:2 WPC+0%S +RS
Curing: 10°C Water Curing



Materials: 1:2 OPC+50%S-40+RS
Curing: 10°C Water Curing

Materials: 1:2 OPC+50%S-40+RS
Curing: 20°C Air Curing

Materials: 1:2 OPC+50%S-40+RS
Curing: 30°C Water Curing

Photo B3 Crushed samples after compressive strength test those cured in different Curing conditions and prepared with different combinations of ground granulated blast furnace slag and oyster shell aggregate.