

Gel Space Ratio Model for MIRHA Foamed Concrete Strength

Rifadli Bahsuan¹, Ridho Bayuaji², Nita Suleman³

¹Engineering Department, Universitas Negeri Gorontalo, Indonesia

²Civil Engineering Department, Institut Teknologi Sepuluh Nopember, Indonesia

³Chemistry Department, Universitas Negeri Gorontalo, Indonesia

Corresponding Author: Rifadli Bahsuan

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ABSTRACT

This paper reports the results of a study undertaken to investigate the effects of non-evaporable water on the strength of foamed concrete incorporating classified and unclassified microwave incinerated rice husk ash (MIRHA). It investigates the relationship between non-evaporable water and compressive strength and presents mathematical models developed to describe this relationship. The compressive strength of the foamed concrete was found to be a function of non-evaporable water and age, with a multiplicative model providing the best fit for all ages up to 180 days. In addition, it was concluded that Powers' equation could effectively predict the compressive strength of foamed concrete mixtures containing MIRHA.

Keywords: Foamed Concrete, Microwave Incinerated Rice Husk Ash (MIRHA), Non-evaporable water content

INTRODUCTION

This paper investigates the relationship between non-evaporable water and compressive strength and presents mathematical models developed to describe this relationship. This part of the study aims to examine the effects of MIRHA addition on non-evaporable water content and its correlation with strength.

The non-evaporable water content is a useful index for indicating the degree of microstructural development and subsequent mechanical properties development in the cement-based mixture.

Chemically combined water is an important type of water to measure because it can be used to quantify the extent of hydration. Unfortunately, there is currently no simple method (drying or otherwise) to separate chemically combined water from gel water, preventing accurate measurement of either component. Consequently, the term "non-evaporable water" is employed as a practical approximation of chemically bound water, given its relative ease of quantification.

The term "non-evaporable water" reflects the amount of water not removed (i.e. evaporated) by a certain drying procedure. The name does not specify which drying procedure should be employed, and various researchers apply different methods. For example, Powers (1958) defined non-evaporable water as the water retained by a sample after drying over a magnesium chloride solution at 23°C. In contrast, Shafiq (1999) and Hobbs (2000) dried samples in an oven at 105°C overnight. A more detailed explanation reveals that the different drying procedures are neither equally effective nor remove the same amount or type of water. Non-evaporable water measurements of the

same specimen may differ depending on the drying method. For comparative purposes, corrections are necessary to account for these differences between the drying methods.

The goal of measuring non-evaporable content is to approximate the amount of chemically bound water. In general, most drying methods are designed to remove free and adsorbed water, leaving only the chemically bound water. Ideal drying methods would be sufficiently effective so that non-evaporable water represents only the chemically combined water. However, researchers have found that different drying methods may either a) remove some chemically bound water, b) fail to evaporate all adsorbed and free water, or c) both (Powers, 1958; Taylor, 1990). In these cases, the non-evaporable water measurement does not exactly equal the amount of chemically bound water. Readers are thus cautioned against interpreting reported non-evaporable water measurements that lack a description of the drying procedure employed.

This paper presents an improved equation to calculate non-evaporable water loss and gel space ratio by considering the effects of different mix designs involving ordinary Portland cement (OPC), MIRHA and the degree of hydration using the volumetric ratio of hydration products. No concrete and hardened cement paste differentiation is required, as the formulation is based on the hydration products. Hardened cement pastes with various mix designs were used to determine the decomposition profile for the hydration products. The resulting gel space ratio model for the different mix designs was then compared with the model Nambiar

and Ramamurthy (2008) proposed

The strength of concrete at any water-cement ratio depends on the degree of hydration, its chemical and physical properties, and the air content of the concrete. Powers related strength to the concentration of solid hydration products within the available space using the gel-space ratio concept (Neville, 1995).

The relationship between strength and gel-space ratio is expressed as strength = X (gel-space ratio)ⁿ, where 'X' is the intrinsic strength of the gel and 'n' is an empirical constant. The gel-space equation considers the degree of cement hydration, thereby incorporating the effect of age into the equation. The volume of cement hydrates (gel volume) is generally taken as 2.06αV_c. In the case of the cement-sand MIRHA mix, the volume of products formed by the pozzolanic reaction is not considered.

$$\text{Space} = 1 - V_{fl} - V_c (1 - \alpha) \quad (1)$$

$$\text{Gel space ratio, } X = \frac{2.06\alpha V_c}{1 - V_{fl} - V_c(1 - \alpha)} \quad (2)$$

Space = 1 - volume of solids that will not be hydrated (fillers) - volume of unhydrated cement. Where V_c is the volume of cement, V_{fl} is the volume of fillers per m³ of concrete, and α is the degree of hydration.

The gel-space ratio was computed for both foamed concrete mixes at different densities and plotted against the experimentally obtained compressive strength, as shown in Figure 1. Compared to cement-fly ash mixes, the gel-space ratio correlates well with the compressive strength of foam concrete with cement-sand mix.

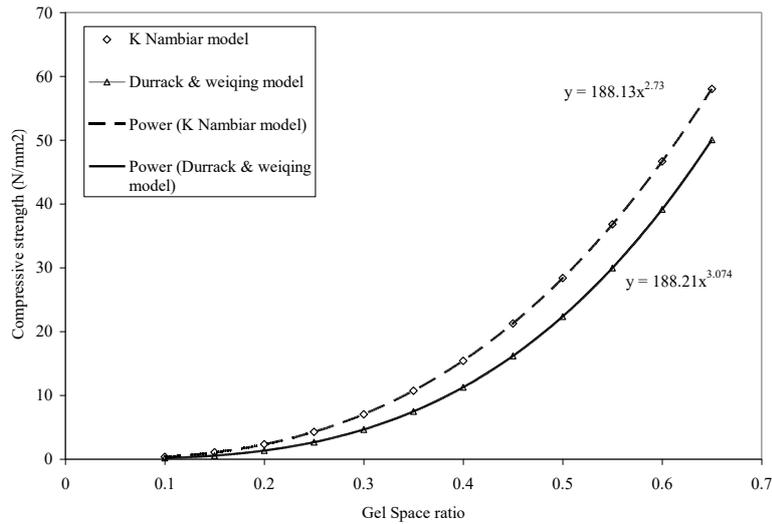


Figure 1. Variation of compressive strength with gel-space ratio for cement-sand mix (Nambiar & Ramamurthy, 2008)

MATERIALS & METHODS

Material

The constituent materials used in the laboratory to produce foamed concrete comprised (i) Portland cement (Ordinary Portland Cement BS EN 197-1), (ii) natural sand, with 100 passing a 425 mm sieve, (iii) MIRHA, with high reactive silica content produced under controlled combustion of

rice husk and (iv) free water (v) superplasticizer. The surfactant used for producing the preformed foam was prepared by aerating palm oil-based LCM at a ratio of 1:30 (by volume), resulting in a foam density of 110 kg/m³. The chemical properties of MIRHA and OPC used are shown in Table 1.

Table 1. Physical and Chemical Properties of OPC Type 1. Adapted from Cement Industries of Malaysia Berhad (CIMA)

Modulus	Lime Saturation Factor	0.96
	Silica Modulus	2.37
	Iron Modulus	1.58
Compressive Strength (N/mm ²)	3 Days	38
	7 Days	46
	28 Days	56
Chemical Ingredients (%)	SiO ₂	19.98
	Fe ₂ O ₃	3.27
	Al ₂ O ₃	5.17
	CaO	63.17
	MgO	0.79
	SO ₃	2.38
	Total Alkalis	0.90
	Insoluble Residue	0.2

Table 2: RHA Chemical Composition*

Chemical Content	Mass content (%)
Silicon dioxide or silica (SiO ₂)	90.75
Aluminum oxide or alumina (Al ₂ O ₃)	0.75
Iron oxide (Fe ₂ O ₃)	0.28
Calcium oxide or lime (CaO)	0.87
Magnesium oxide or magnesia (MgO)	0.63

Sodium oxide (Na ₂ O)	0.02
Potassium oxide (K ₂ O)	3.77
Equivalent alkalis (Na ₂ O + 0.658 K ₂ O)	2.50
Titanium oxide (TiO ₂)	0.02
Phosphorous oxide (P ₂ O ₅)	2.5
Manganese oxide (MnO)	0.08
Sulfur trioxide (SO ₃)	0.33
Other	
Sulfur (S)	< 0.01
Carbon (C)	0.15
Chloride (Cl):	110 g/t

* Test results obtained from XRF's Universiti Teknologi Petronas, Malaysia.

Design Experiments

The most important stage in designing the experiment lies in selecting the control factors. As many variables as possible should be included to identify non-significant variables early.

Genichi Taguchi developed the Taguchi method as a process optimization technique during the 1950s (Roy, 2010). Taguchi's approach to parameter design provides engineers with a systematic and efficient method for determining near-optimum design parameters for performance and cost. In this study, the following parameters were considered in the mix proportions: Microwave incinerated Rice Husk Ash contents (MIRHA), water cementations ratio (w/c), sand cement ratio (s/c), superplasticizer content (SP), and foam content (FC). The details of the Taguchi experimental design used in this study are described in a previous paper (Bayuaji & Nuruddin, 2009; Bayuaji & Nuruddin, 2014).

Preparation of Sample

The mix proportions of the binders are presented in Table 4. The mixes were prepared over approximately 5.5 minutes using a rotating planetary mixer. The fine aggregate was first mixed with 1/2 of water, then PC and MIRHA were added. Subsequently, the remaining water and chemical admixtures were pre-mixed and added to the mixture. Finally, the appropriate foam volume was generated and added immediately to the base mix, then mixed. There were no visible signs of the foam on the surface, and the foam was

uniformly distributed and fully incorporated into the mixture.

After mixing, six 50 mm cube samples were cast from each concrete mix for compressive strength testing at 3, 7, 28, 90, and 180 days. After the compression test, the fractured pieces of the cubes were preserved for additional analyses. The samples were soaked in acetone in order to stop the hydration reactions. The specimens were demolded 24 hours after the casting and placed in a water tank maintained at 20 ± 2 °C.

The loss on ignition method using Oven Dry/Furnace Ignited (OD/FI) and Thermogravimetry (TGA) was employed to determine the non-evaporable water (NEW) content at various selected hydration ages. Small fragments of the samples (approximately 1–2 mm in size) cured in saturated limewater were pulverized and soaked in acetone to stop further hydration. The pulverized samples were first heated in an oven at 105 °C for 24 hours, followed by heating in a muffle furnace at 1050 °C for 3 hours. The NEW content (wn) was obtained as the difference in mass between the sample heated at 105 °C and 1050 °C normalized by the mass after heating to 1050 °C. Corrections were applied to account for the loss on ignition of unhydrated foamed concrete (or of both the unhydrated foamed concrete and the CRM multiplied by their respective mass fractions).

RESULT AND DISCUSSION
Compressive Strength

The results of the compressive strength test of the pastes are shown in Table 3.

Table 3. Test results of compressive strength for MIRHA FC

Code	Compressive strength (N/mm ²)				
	3d	7d	28d	90d	180d
LWFC-1	30.03	36.35	55.14	66.13	83.87
LWFC-2	43.91	56.08	68.89	86.71	79.19
LWFC-3	18.79	20.60	25.19	25.89	27.33
LWFC-4	10.36	11.71	13.76	15.45	16.03
LWFC-5	24.76	25.34	28.78	47.07	52.74
LWFC-6	22.34	23.92	22.33	26.97	30.71
LWFC-7	37.51	40.22	54.81	67.23	73.52
LWFC-8	43.03	54.48	63.87	64.04	81.98
LWFC-9	20.20	23.37	28.73	47.38	47.53
LWFC-10	24.06	29.61	36.62	45.67	48.21
LWFC-11	8.34	13.14	18.18	21.37	21.41
LWFC-12	22.42	29.04	40.14	49.54	51.24
LWFC-13	15.60	20.22	27.84	29.17	31.76
LWFC-14	24.46	25.79	30.77	35.18	39.00
LWFC-15	6.49	9.63	9.84	10.51	15.86
LWFC-16	15.08	19.29	25.48	25.69	26.27

Table 4 shows the main effect plots for compressive strength at 3, 7, 28, 90 and 180 days, obtained using the orthogonal-array

procedure. The development of compressive strength of foamed concrete is illustrated in Figure 2.

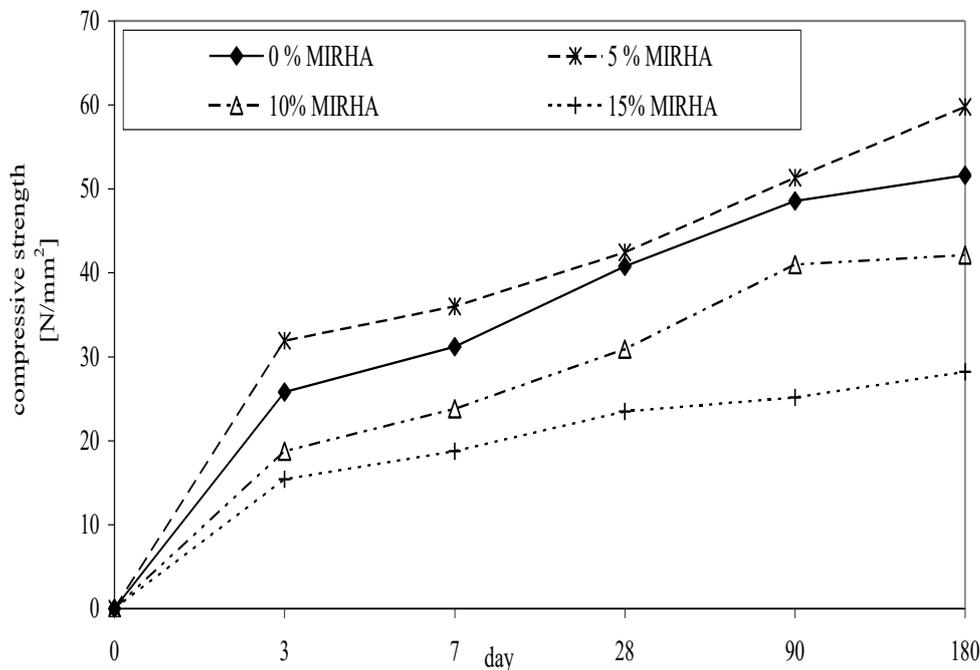


Figure 2. Compressive strength development of foamed concrete

Table 4. Test results of compressive strength for MIRHA FC using orthogonal array analysis

Time (day)	Compressive Strength (N/mm ²)																			
	MIRHA (%)				w/c				s/c				SP (%)				FC (%)			
	0	5	10	15	0.3	0.35	0.4	0.45	0.25	0.5	0.75	1	1	1.5	2	2.5	20	25	30	35
3	25.8	31.9	18.8	15.4	24.4	26.6	21.9	18.5	22.6	28.7	17.8	22.7	14.8	20.7	27.7	28.6	25.9	29.2	19.8	17.0
7	31.2	36.0	23.8	18.7	30.0	31.1	25.4	24.0	26.3	33.9	20.9	28.6	17.2	23.7	36.0	32.9	32.5	34.7	23.4	19.0
28	40.7	42.4	30.9	23.5	36.9	37.1	33.3	26.7	35.1	39.7	27.0	35.8	18.7	29.0	44.7	45.2	41.4	44.5	28.9	22.9
90	48.5	51.3	41.0	25.1	48.5	43.1	39.4	39.9	47.4	48.6	31.2	38.7	25.1	36.1	50.3	54.5	46.6	56.8	32.9	29.8
180	51.6	59.7	42.1	28.2	49.8	49.0	42.4	44.1	54.0	49.3	34.5	43.9	27.5	38.6	53.6	61.9	57.5	56.6	35.3	32.3

The compressive strength of the control foamed concrete is lower than that of foamed concrete containing 5% MIRHA as cement replacement. Starting at 3 days, the 5 % MIRHA shows greater strength compared to both the 10% and 15 % MIRHA mixes, indicating enhanced cement hydration due to pozzolanic activity, as shown in Figure 1.

Non-evaporable water by Oven Dry/Furnace Ignited (OD/FI)

Non-evaporable water (NEW) contents (wn) of cement pastes, determined by OD/FI, are commonly used to assess the degree of hydration. In this study, the optimal mix proportion levels were investigated to maximize NEW values using the Taguchi method. The results of the wn content are shown in Table 5. Table 6 shows the main effect plots for non-evaporable water at 3, 7, 28, 90 and 180 days, based on the orthogonal array procedure.

Table 5. Test results of NEW for MIRHA FC by OD/FI

No	Code	3day	7day	28Day	90day	180day
		(wn/c) %				
1	LWFC-1	12.89	13.99	16.80	19.45	19.88
2	LWFC-2	13.92	17.44	18.20	20.83	21.20
3	LWFC-3	14.48	16.55	17.54	20.21	22.42
4	LWFC-4	13.16	14.55	18.74	21.10	22.98
5	LWFC-5	14.15	14.82	19.48	20.31	24.58
6	LWFC-6	15.09	18.80	21.21	22.44	24.03
7	LWFC-7	14.70	15.62	18.74	21.46	22.84
8	LWFC-8	16.19	18.01	19.05	24.49	25.88
9	LWFC-9	13.50	16.12	19.83	19.93	22.94
10	LWFC-10	13.39	18.79	21.41	23.34	24.96
11	LWFC-11	12.32	16.96	20.30	22.76	25.34
12	LWFC-12	16.68	17.12	17.33	17.64	20.45
13	LWFC-13	15.69	15.64	22.34	24.21	25.73
14	LWFC-14	13.18	19.21	20.51	23.41	24.45
15	LWFC-15	12.46	17.58	17.78	19.04	21.30
16	LWFC-16	12.41	17.27	20.48	21.94	22.16

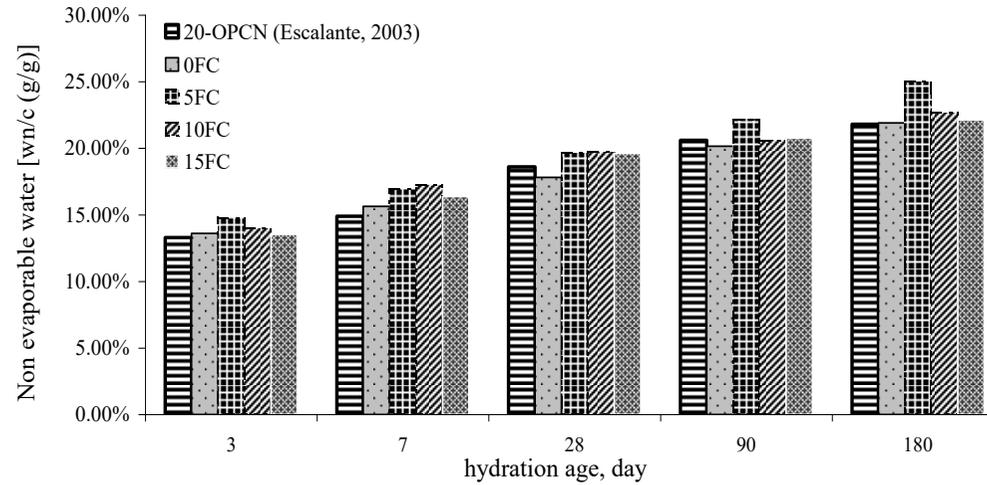


Figure 3. NEW Content in Foamed Concrete

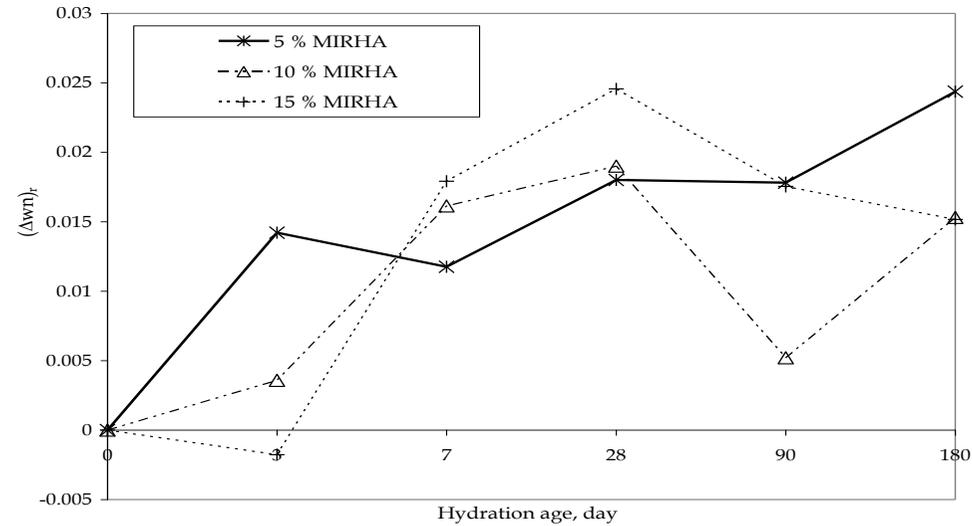


Figure 4. Change in Non-Evaporable Water Content a Result of Hydration from Replacement Material in Foamed Concrete with MIRHA

Figure 3 depicts the development of non-evaporable water content (wn) in plain foam concrete, which closely follows the trend observed in neat ordinary Portland cement (Escalante-Garcia, 2003). The MIRHA powder-modified foamed concrete showed a higher non-evaporable water content value compared to the plain foamed concrete. After 28 days, the foamed concrete containing 5% MIRHA showed higher wn than those with 10% and 15% MIRHA. Figure 4

presents the values of relative change in (Δw_n) r plotted against the age of hydration for MIRHA powder-modified foamed concrete. Further, in Fig. 3, up to approximately 28 days, the (Δw_n) r values for foamed concrete modified with 10% and 15% MIRHA powder increase, indicating increased cement grain hydration due to the higher effective w/c ratio.

Table 6. Test Results of Non-Evaporable Water for MIRHA FC using Orthogonal Array Analysis

Time (day)	wn/c (g/g) (%)																			
	MIRHA (%)				w/c				s/c				SP (%)				FC (%)			
	0	5	10	15	0.3	0.35	0.4	0.45	0.25	0.5	0.75	1	1	1.5	2	2.5	20	25	30	35
3	13.6	14.8	14.0	13.5	14.3	14.1	14.2	13.3	14.1	13.9	13.5	14.5	13.6	13.7	14.3	14.4	13.5	13.7	15.5	13.2
7	15.6	17.0	17.2	16.4	16.9	16.4	16.1	16.8	15.3	17.5	16.7	16.7	16.8	17.0	17.0	15.4	17.1	16.6	17.0	15.5
28	17.8	19.6	19.7	19.6	18.2	18.6	20.3	19.7	19.6	19.7	18.6	18.9	19.4	19.7	20.0	17.7	18.8	19.3	19.6	19.1
90	20.2	22.2	20.6	20.8	19.2	20.7	22.1	21.6	20.9	20.6	20.9	21.3	20.6	21.1	22.7	19.2	21.2	20.8	21.0	20.6
180	21.9	25.0	22.7	22.1	21.8	22.9	24.3	22.7	23.1	22.0	23.5	23.1	23.1	23.0	24.2	21.4	22.4	22.9	22.9	23.4

Following 28 days, (Δw_n) r values are observed to decrease, showing that the secondary reaction of the replacement material, if any, does not compensate for the dilution effect. However, for the paste modified with 5% MIRHA powder, (Δw_n)r consistently increases over time. This indicates that a 5% cement replacement with MIRHA powder can be considered effective at a w/cm of 0.4.

Non-evaporable water by TGA

Data on non-evaporable water measured using TGA equipment is shown in Table 7. Fig 4 shows the change in non-evaporable water content as a result of the replacement material hydration for foamed concrete with 5% MIRHA, measured by TGA. This is evident in the paste modified with 5% MIRHA powder, where (Δw_n) r increases consistently over time.

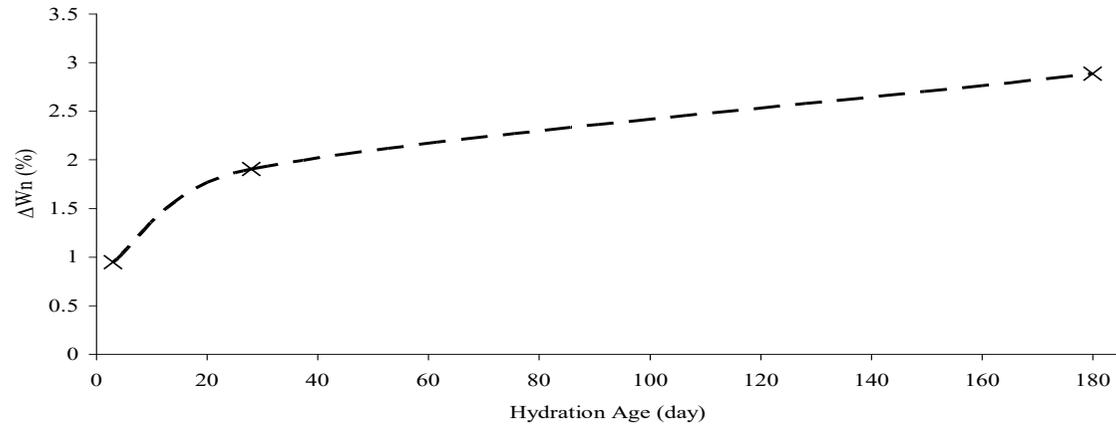


Figure 5. Change in Non-Evaporable Water Contents as a Result of Replacement Material Hydration for Foamed Concrete with 5% MIRHA Measured by TGA

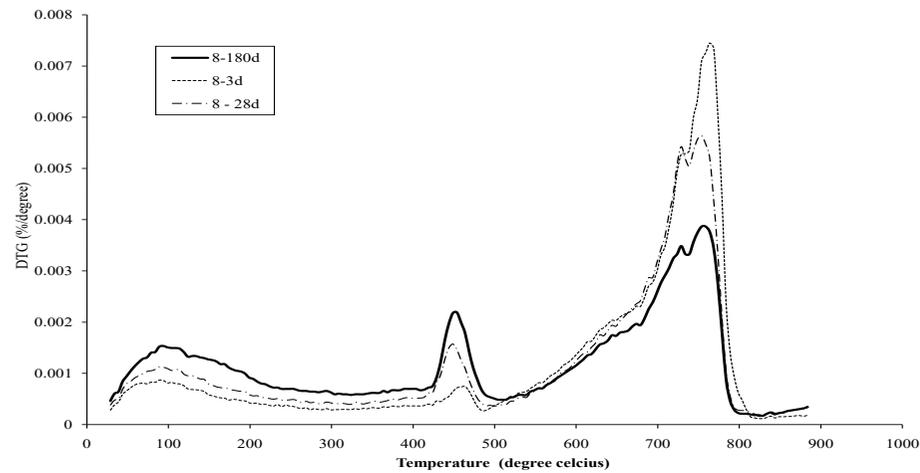


Figure 6. DTG curves of foamed concrete with 5% MIRHA and w/c=0.35, obtained at a linear heating rate of 20°C/min under an air atmosphere.

Figure 6 shows the thermal DTG curves obtained by heating samples of foamed concrete incorporating 5% MIRHA with a water/cement ratio of 0.35, subjected to curing periods of 3, 28 and 180 days. Several losses appear on these curves, with three main decomposition regions identified in the hardened foamed concrete incorporating MIRHA: 105-440°C, 440-500°C and 500-900°C.

The first region corresponds to the dehydration of C-S-H, the second to the dehydroxylation of CH, and the third to the decarbonation of

calcium carbonate. The dehydroxylation process shows that CH content is higher at 180 days compared to the samples at earlier ages. This phenomenon indicates that more CH was produced as a result of reactions with MIRHA over time. However, the decarbonation process was reversed, exhibiting the opposite trend: DTG values were higher for the younger samples.

Table 8. Test results of NEW for MIRHA FC by TGA

No. Exp.	3 days				28 days				180 days			
	CSH/Afm bound water	CH bound water	Misc	wn/c	CSH/Afm bound water	CH bound water	Misc	wn/c	CSH/Afm bound water	CH bound water	Misc	wn/c
1	9.123	0.609	0.016	9.748	10.653	1.428	0.011	12.092	13.480	2.468	0.228	16.176
2	8.860	0.789	0.101	9.750	10.392	1.234	0.158	11.784	13.354	2.447	0.656	16.458
3	8.375	0.513	0.403	9.292	11.187	1.288	0.519	12.994	13.584	2.162	0.119	15.865
4	8.886	0.402	0.158	9.446	10.448	0.916	0.286	11.649	13.873	2.138	0.484	16.495
5	6.886	2.278	0.132	9.295	9.544	2.148	0.365	12.057	12.800	2.040	0.705	15.546
6	7.647	1.574	0.161	9.382	11.012	1.465	0.180	12.656	18.486	1.253	0.180	19.919
7	8.855	1.182	0.101	10.138	9.678	1.095	0.332	11.105	14.363	0.875	0.359	15.597
8	9.335	1.811	0.138	11.284	14.075	1.704	0.344	16.122	16.389	1.605	0.425	18.419

Compressive Strength vs. Non-Evaporable Water Content

More significant than the individual trends of compressive strength and non-evaporable water contents over time is the relationship between these two measured properties. This relationship (i.e. compressive strength versus non-evaporable water content) is shown graphically in Figure 7.

Degree of Hydration

The experimentally determined degrees of hydration for MIRHA-modified foamed concrete are shown in Fig 7. It can be observed that the overall degrees of hydration are lower for most of the modified pastes. Further insight into this behavior can be obtained by using the degree of hydration values to predict other material properties, such as compressive strength, and comparing these predicted values with the measured ones.

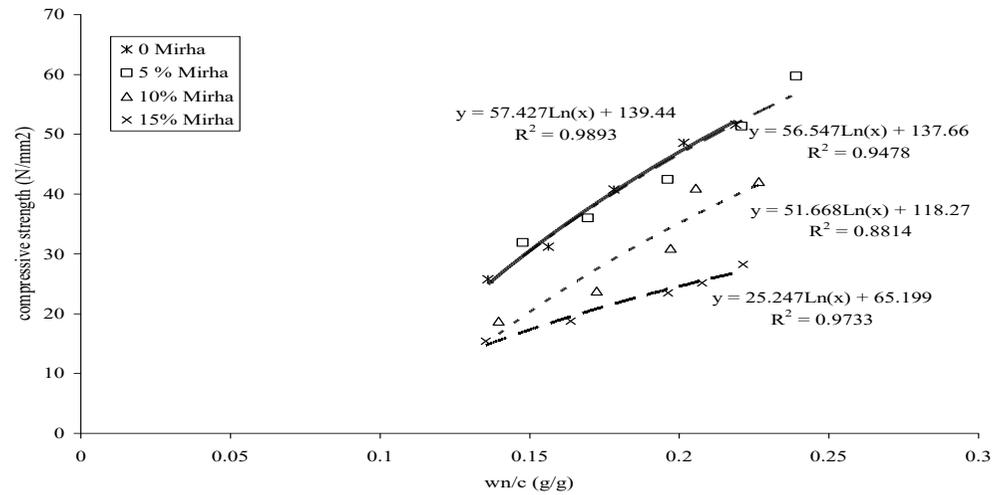


Figure 7. Compressive strength versus non-evaporable water content for Experimental Foamed Concrete with and without MIRHA

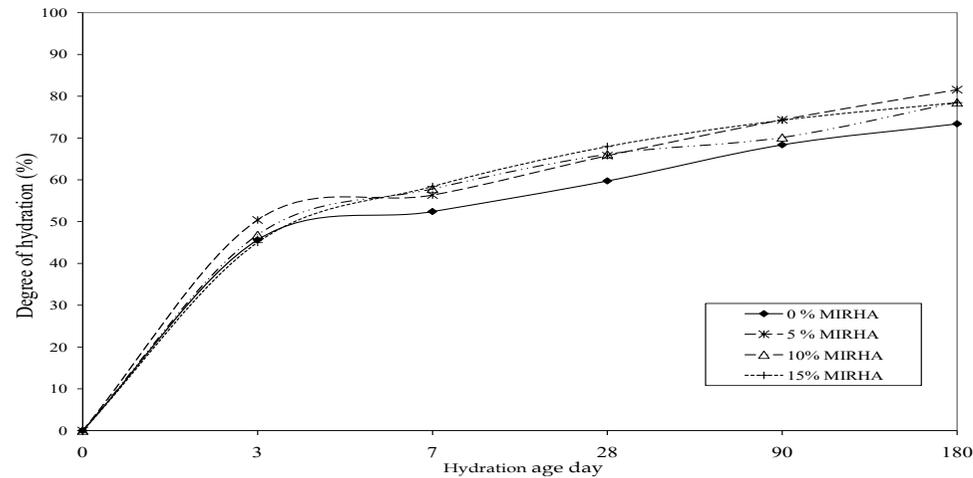


Figure 8. Degree of hydration of foamed concrete with MIRHA

Gel-space ratio model

The gel-space ratio was computed for both the mixes of foamed concrete at different densities and plotted against the experimentally obtained compressive strength, as shown in Fig.8. The relationship between compressive strength and gel-space ratio in foamed concrete with and without MIRHA is expressed as follows:

1. $f_c = 186 \times 1.9625$, $R^2 = 0.9906$ (foamed concrete without MIRHA)
2. $f_c = 145.53 \times 1.6771$, $R^2 = 0.9764$ (foamed concrete with 5%MIRHA)
3. $f_c = 150.42 \times 2.2036$, $R^2 = 0.9376$ (foamed concrete with 10%MIRHA)
4. $f_c = 30.068 \times 0.8718$, $R^2 = 0.9272$ (foamed concrete with 15%MIRHA)

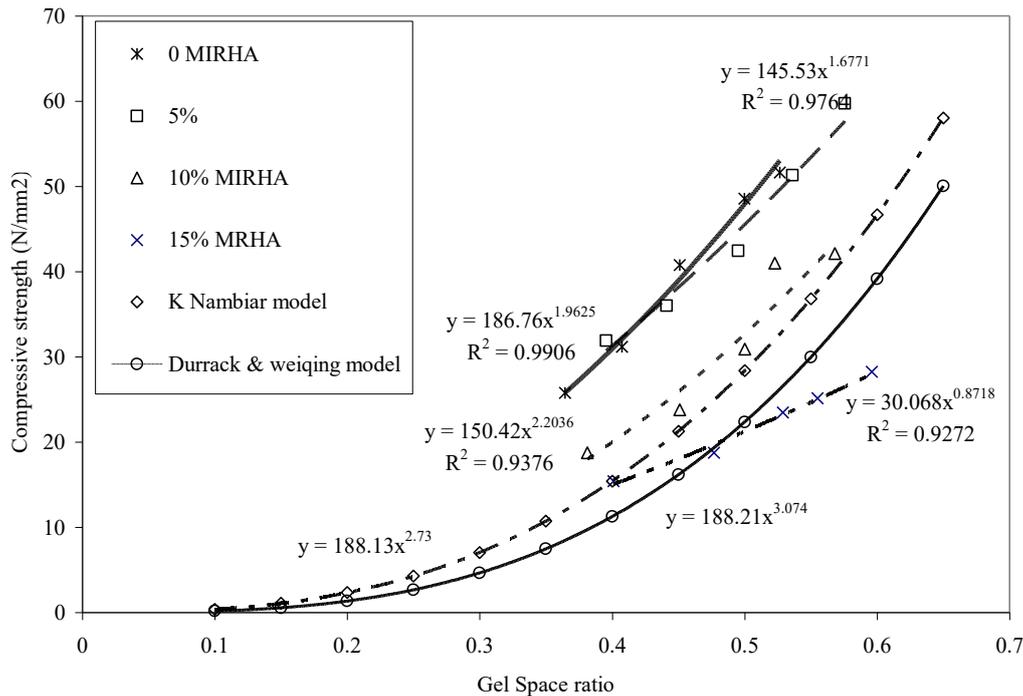


Figure 9. Compressive strength versus Gel Space ratio for Experiment Foamed Concrete with and without MIRHA

CONCLUSION

The model relationship between compressive strength and gel-space ratio developed by Powers (1958) for foamed concrete with and without MIRHA can be established through non-evaporable water analysis using OD/FI and TGA techniques.

Declaration by Authors

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