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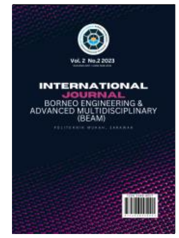

Preliminary Study on Response of Different Water-Cement Ratio and Curing Conditions on Concrete Properties

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Abstract

The water-to-cement ratio (w/c ratio) is a critical parameter in the formulation of mortar and concrete. The w/c ratio is a fundamental factor that significantly affects the performance and properties of the final product. This study investigated the influence of different w/c ratios and curing conditions on concrete properties. The preliminary test was conducted on coarse and fine aggregate by complying with ASTM C33. The concrete proportion ratio of 1:2:4 was adopted by mixing with various amounts of distilled water to create ratios of 0.5, 0.6, 0.7, and 0.8. The hardened concretes were divided into two types of curing conditions (pond curing and burlap curing). Compressive strength, sorptivity, and carbonation tests were conducted by complying with the concrete's standard procedure to determine the concrete's properties. This research has revealed that a higher w/c ratio contributes to higher porosity and negatively impacts its strength. The higher w/c ratio has decreased compressive strength and increased water filtration (sorptivity) and carbon dioxide ingression (carbonation). Based on the results, lower w/c ratio with pond curing showed better concrete physical and chemical properties at 28th days.

Keywords: - Curing condition, water-to-cement ratio, concrete properties

1. Introduction

Concrete is a composite material composed of cement, water, aggregates, and often additional additives. The properties of concrete that are resistant to extreme weather, durable, insect-resistant, non-flammable, and adaptable for different designs and finishes make concrete a prime choice of building materials by architects and engineers.

In concrete mixing, the water-to-cement (w/c) ratio is considered one of the major factors influencing concrete properties. During the hydration phase, water will react with the cement compound to form calcium-silicate hydrate (C-S-H) and calcium hydroxide ($Ca(OH)_2$). Inadequate water will cause poor workability (Masum & Manzur, 2019), increase porosity (Jagtap et al., 2020), greater permeability (Serag et al., 2019), cracking (Huang et al., 2022) and lead to a loss in strength of concrete. In addition, Oikonomopoulou et al. (2022) also point out that the compressive and split tensile strength reduced to 15 % and 26.9 %, respectively, due to the low w/c ratio.

The w/c ratio may vary, influenced by raw materials (types of binder, fine and coarse aggregate properties, water), mix design proportions, and admixtures. It was believed that the size and types of raw material would influence the amount of water needed and change the mechanical properties of concrete. Nematollahzade et al. (2020) investigated the effect of the w/c ratio on self-compacting concrete and discovered that as the w/c ratio increased, it gave a favourable workability feature, but the compressive strength declined. The study by Langhah & Saand (2020) stated that the 0.5 w/c ratio was incompatible with the increasing amount of eggshell powder as a partial cement replacement. Rashad & Sadek (2020) found that concrete with 50 % granulated blast-furnace slag based on a w/c ratio of 0.5 gives concretes the highest mechanical strength. Sangeetha et al. (2022) reported a concrete mix design of 5 % of seashell powder and 10 % seashells aggregate with 0.5 w/c ratios showed the highest compressive strength among modified concrete in 90 days period curing days but still lower than the control specimen.

Other than quantity, water quality in concrete mixing is important in determining concrete properties. Water consists of impurities such as chloride, sulphate, organic matter, dirt, clays, biological contaminants, and metals that will influence the mechanical strength, setting time and durability (Kucche et al., 2015). Ali et al. (2020) studied the effect of well water in mixing and curing concrete. They found that the strength of concrete is lower and decreases linearly when it is cured using well water. Then, Hassani et al. (2020) revealed in the High-Resolution Scanning Electron Microscopy (HRSEM) image that the increasing penetration of chloride ions is due to increasing voids and porosity found on the surface and its consequence of impurities in wastewater.

During the hydration process, the formation of calcium silicate hydrate (C-S-H) is a consequence of the reaction between calcium oxide (cement) and silica (sand) and water as an activator. The properties of C-S-H play a critical phase in determining the mechanical strength of concrete (Li et al., 2021). Zheng et al. (2021) have revealed higher w/c ratio creates a higher number and size of pore spaces in scanning electron microscopy (SEM) images. In addition, water in capillaries evaporated to the surroundings due to lower relative humidity and high temperatures. This condition may influence void ratios.

Concrete curing is a technique for moistening concrete during hydration to develop desirable strength. During the early hydration stage, the evaporated water might not be replaced adequately (Allam et al. 2020; Khan et al. 2021). The curing procedure may vary depending on the concrete's size, form, or in-situ planting. Previous studies employed the wet burlap method, ponding method, plastic membrane method, sprayed method, and others (Nasir et al., 2022; Nadir et al., 2022; Secanellas et al., 2019; Ren & Houben, 2020).

Numerous studies have been conducted on concrete, but the characteristics of different w/c ratios and curing conditions are not fully understood. This research investigated the effect of different curing conditions (pond curing and burlap curing) with different w/c ratios (0.5, 0.6, 0.7 and 0.8) to concrete’s physical properties (workability, compressive strength, sorptivity) and chemical properties (carbonation), from the early hardening stage up to 28 days. The mixing design ratio 1:2:4 (cement:fine aggregate:coarse aggregate) was adopted. All concrete specimens were cured with distilled water at ambient temperature to avoid impurities or temperatures that might interfere with the experimental results.

2. Materials and Methodology

The material used is cement (ASTM C150 – Standard Specification for Portland Cement), fine and coarse aggregate (ASTM C33 – Standard Specification for Concrete Aggregates), and distilled water. The laboratory test complied with ASTM C143 (Slump of Hydraulic Cement Concrete test), ASTM C31-19 (Standard Practice for Making and Curing Concrete Test Specimens in The Field), BS EN 12390-3:2021 (Testing Hardened Concrete - Compressive Strength Test), ASTM C1585 (Sorptivity) and BS EN 14630: 2006 (Carbonation).

2.1 Raw Material Preparation

a. Cement

The locally manufactured Ordinary Portland cement Type I (NS cement) was selected. The composition of Portland cement reported by Zhao et al. (2020) is tabulated in Table 1.

Table 1. Chemical composition of Ordinary Portland Cement Type I (Zhao et al., 2020)

Chemical name	Percentage (%)
Calcium Oxide (CaO)	64.18
Silicon Dioxide (SiO_2)	22.02
Aluminium Oxide (Al_2O_3)	3.50
Iron Oxide (Fe_2O_3)	0.96
Magnesium Oxide (MgO)	2.65
Sulfur Trioxide (SO_3)	3.25
Sodium Oxide (Na_2O)	0.20
Titanium Dioxide (TiO_2)	0.24

b. Fine Aggregate and Coarse Aggregate

The fine and coarse aggregate was dried in a ventilated oven at 105 ± 5 °C for 1 hour to remove excess water and the moisture accumulated in the sand particles to obtain the actual quantity of water. The 1000 g and 5000 g of dried fine and coarse aggregate are sieved using a mechanical sieve shaker and left to vibrate for 5 minutes. The size of coarse and fine aggregates selected is in the range of 10 mm to 20 mm and less than 4.75 mm, respectively.

2.2 Mixing Formulation and Specimens Manufacturing

This study adopted a mixing ratio of 1:2:4 with four varying w/c ratios with three replications. As Thillo et al. (2021) and Hosseinzadeh et al. (2019) recommended, the concrete was mixed by the hand-mixing method to avoid air-entrapped during rotation mixing. All solid ingredients are dry-mixed for approximately two minutes. Once the dry mix was homogenous, distilled water was added as a binder activator to avoid any chemical substance that may influence results. The mixed proportion used in this study is shown in Table 2.

Table 2. The mixed proportion used in this study

Specimen	Cement (g)	Coarse Aggregate (g)	Fine Aggregate (g)	Water (ml)
Pond curing (pc)				
$S_{0.5pc}$	1000	2000	4000	500
$S_{0.6pc}$	1000	2000	4000	600
$S_{0.7pc}$	1000	2000	4000	700
$S_{0.8pc}$	1000	2000	4000	800
Burlap curing (bc)				
$S_{0.5bc}$	1000	2000	4000	500
$S_{0.6bc}$	1000	2000	4000	600
$S_{0.7bc}$	1000	2000	4000	700
$S_{0.8bc}$	1000	2000	4000	800

The slump test determined the workability of the fresh concrete by complying with ASTM C143 – Slump of hydraulic-cement concrete. A 300 mm conical frustum with top and bottom open at both ends, 100 mm and 200 mm diameters, respectively, was placed on its plate on a flat surface. This cone was packed with three phases of fresh concrete with 25 times tapping at each layer by a long bullet nose metal rod. Then, the cone was steadily lifted vertically without interruption, the conical frustum was placed inversely next to the sample, and the slump of fresh concrete was measured by a ruler. The slump test result is shown in Fig. 1 with different water ratios.

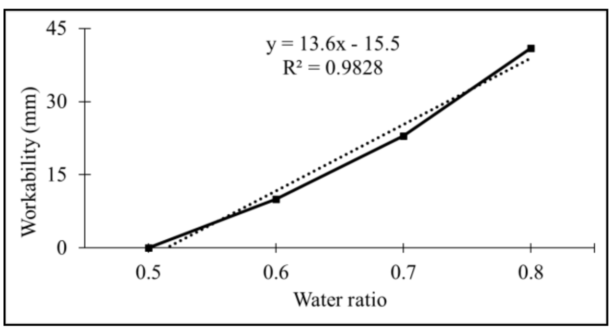

Fig. 1. Slump test results

A standard size 150 mm x 150 mm x 150 mm concrete was cast using steel mould for each water-cement ratio for three replications. Afterward, specimens are removed from the mould after 24 ± 8 hours (ASTM C192) and marked before curing for up to 28 days. The specimens were divided into two types of curing: pond curing and burlap curing.

For pond curing, specimens were fully immersed in a container with distilled water at ambient temperature (25 ºC) following ASTM C31-19, as shown in Fig. 2. The metal rods were placed under specimens to allow water absorption on the surfaces. While for burlap curing, the specimens were covered with damp gunny cloth and sprayed with distilled water twice a day until 28 days (Zeyad et al., 2022). The specimens with burlap curing were placed sheltered to avoid excess evaporation.

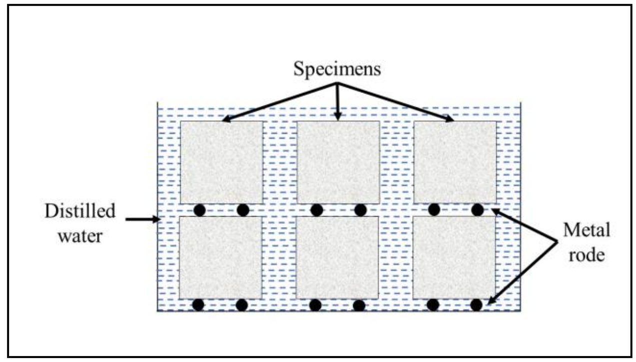

Fig. 2. Pond curing set-up

2.3 Physical and Chemical Properties

a. Compressive Strength

All specimens were tested with compression tests in compliance with BS EN 12390-3:2021 using an automatic compression testing machine. The platens were cleaned before the specimen was placed at the centre of the platens. Force was applied at the top and bottom of the specimen with a constant rate in the range of 0.2 N/mm2 to 1.0 N/mm2 and increased continuously until it reached the maximum force. The compressive strength was evaluated at ages 7, 14, and 28 days.

b. Sorptivity

Each specimen's fluid absorption by capillary was observed by complying with ASTM C 1585. In this test, distilled water was chosen as fluid. Before this test was carried out, all 28th days specimens were dried in a drying oven at 105 ± 5 °C for 30 minutes. For accuracy, all vertical surfaces of the specimen were wrapped with masking tape to avoid water immersion on side surfaces. As shown in Fig. 3, specimens were held on a pair of metal rods and allowed to immerse in a 3 ± 0.5 mm depth of distilled water. Water absorption readings are taken every 1, 5, 10, 20, and 30 minutes. The sorptivity values were determined by Equations 1 and 2.

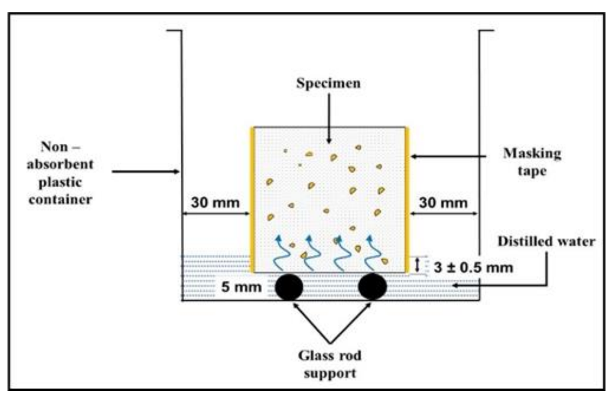

Fig. 3. Sorptivity test setting up

$$S = I/(t)^{0.5} \quad (1)$$
$$I = m_t/(a \times d) \quad (2)$$

Where;
S = sorptivity
I = the absorption
t = Time (s)
mt = the change in specimen mass in grams, at the time, t
a = surface area (mm²)
d = water filtration depth (mm)

c. Carbonation

After the curing process, all specimens are left in an atmospheric environment for the carbonation process. To ensure that the carbonation process occurs evenly on each surface, specimens are placed on metal rods, as shown in Fig. 4 below. After the 28th day, the specimens were split into two parts. The new broken concrete area was sprayed with colourless phenolphthalein ($C_{20}H_{14}O_4$) solution by complying with BS EN 14630: 2006. The uncarbonated concrete area instantly turned to a pink stain, while the carbonated area remained colourless. The carbonated area's depth a, b, c, and d (see Fig. 4) was measured using a Vernier calliper to get accuracy. The carbonation rate was measured as in Equation 3.

$$Carbonation\ rate = \frac{Average\ carbonation\ depth\ (mm)}{Days} \quad (3)$$

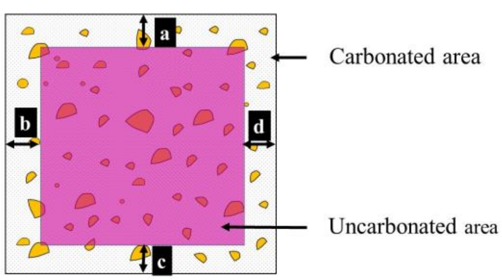

Fig. 4. Carbonation measurement depth

3. Result and Discussion

3.1 Compressive Strength

The compressive strength test results are illustrated in Fig. 5. Based on the graph, the strengths of all specimens increased with age but decreased as the w/c ratio increased. Cao et al. (2019) & Rao et al. (2021) point out that a high w/c ratio will weaken the bonding matrix, and increase the void ratio, resulting in weakening the concrete. In addition, the lower w/c ratio will also result in high compressive strength, low drying shrinkage, and decreased workability (Qin et al., 2022). On the other hand, the graph showed that the strength of all specimens with burlap curing is slightly lower than those with pond curing.

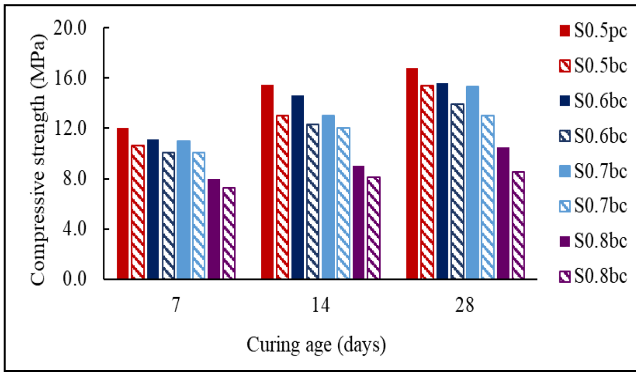

Fig. 5. Compressive strength results

3.2 Sorptivity

Based on the graph in Fig. 6, the sorptivity increased dramatically as the w/c ratio increased. The water filtration by capillaries is higher as the w/c ratio increases and exhibit high porosity. Previous researchers have reported a w/c ratio (Zhou et al., 2020), raw material properties (Razali et al., 2023), aggregate sizes (Zhang et al., 2021), and mixing proportion (Yeih et al., 2019) have influenced the concrete's porosity. Liu et al. (2019) emphasize that greater accessible porosity will lead to great water transportation. They claimed that water diffusivity increases uniformly with the increase of porosity. Free water (not used in the hydration process) in the mixing will evaporate to the surroundings and leave voids and capillaries (Malecot et al., 2018; Muslim et al., 2020).

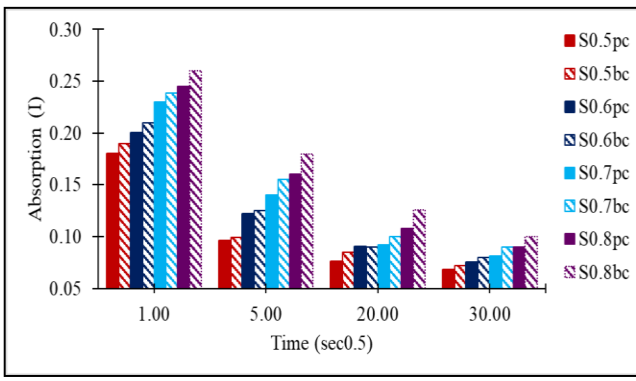

Fig. 6. Sorptivity test results

3.3 Carbonation

The physical observation of the carbonation depth rate is shown in Fig. 7. From the graph, it can be observed that the carbonation rate decreased as the age increased. Then, the graph also showed that the specimens with pond curing have lower carbonation rates than those with burlap curing.

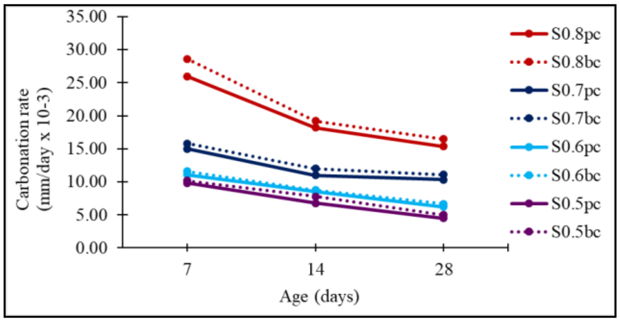

Fig. 7. Carbonation test results

Carbonation is a reaction of carbon dioxide with calcium hydroxide in concrete to produce calcium carbonate and water (see Equation 4). According to Wolińsk et al. (2018), the variables that might influence carbonation rates are carbon dioxide concentration, relative humidity, curing condition, types of cement, porosity, admixtures, and w/c ratio. In this case, the carbonation rate is believed to increase as the w/c ratio consequenced to high porosity. A similar result was obtained by Al-Ameeri (2021), who claimed higher w/c ratio will accelerate carbonation rates.

$$C_a(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2 0 \quad (4)$$

4. Conclusion

The value of the w/c ratio in concrete mix and curing condition has significantly influenced the characteristics of the hardened concrete. This study has provided valuable insights into the relationship between the amount of water and cement in concrete mixtures and their resulting properties, such as workability, strength, durability, and shrinkage characteristics.

A lower w/c ratio generally leads to higher compressive strength and improved durability due to reduced porosity and improved cement hydration. However, a lower w/c ratio may also decrease workability, making the mixture more challenging to handle and place.

Conversely, a higher w/c ratio improves workability by increasing the flowability of the concrete, making it easier to mix and place. However, excessive water content can result in weaker, more porous concrete with reduced long-term durability and increased shrinkage. Excessive water evaporates to the surrounding during the early hardening stage and leaves air voids that might result in a crack. Then, the high amount of void ratios significantly increases the interconnected pores and the number of capillaries, negatively impacting the mechanical properties of concrete. The capillaries will act as a transporter of water and carbon dioxide into the concrete and will cause weakness in the concrete.

According to the results, the mechanical strength of concrete with different curing methods is slightly different. The ponding curing gives a higher compressive strength result, lower water filtration, and lower carbonation rate. It is believed that the evaporated water for the burlap curing method during the early hydration stage might not be adequately replaced. On the other hand, for burlap curing, it is recommended to spray burlap severally in the early stage to keep adequate water for hydration.

The experimental findings emphasize the importance of finding an optimal balance between workability and desired performance characteristics when selecting the appropriate w/c ratio for a specific application. This requires considering the desired strength, exposure conditions, aggregate properties, and any additives or admixtures used. By understanding the significance of the w/c ratio and its effects on the concrete, engineers and concrete technologists can make informed decisions regarding mixture design, leading to the development of high-quality, durable, and workable concrete suitable for various construction applications.

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