

Performance of Concrete Made with Different Coarse Aggregate Particle Sizes under Sulfate Solution

Trong-Phuoc Huynh^{1*}, Si-Huy Ngo², Chao-Lung Hwang³

¹ Department of Rural Technology, College of Rural Development, Can Tho University, Can Tho City, Vietnam.

² Department of Engineering and Technology, Hong Duc University, Thanh Hoa City, Vietnam.

³ Department of Civil and Construction Engineering, National Taiwan University of Science and Technology, Taipei City, Taiwan.

* Corresponding author. Tel.: (+84)985191377; email: htphuoc@ctu.edu.vn

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Abstract: This paper presents the result of an investigation on the performance of concrete produced with different coarse aggregate sizes (CAS) and fully immersed in 5% sodium sulfate solution. Concrete mixtures were prepared with two water-to-binder ratios of 0.35 and 0.45 using four different maximum particle sizes (D_{\max}) of coarse aggregates (9.5 mm, 12.5 mm, 19 mm, and 25 mm). Test results indicate that the workability of concrete increases with increasing the CAS. Concrete made with D_{\max} of 12.5 mm shows the highest compressive strength, whereas concrete made with D_{\max} of 25 mm shows the lowest compressive strength. In addition, the compressive strength of concrete immersed in sulfate solution reduces around 8–13% in comparison with that of concrete cured in water. Moreover, all of the concrete samples perform good durability with ultrasonic pulse velocity values of all greater than 4200 m/s.

Key words: Concrete, coarse aggregate size, sulfate solution, compressive strength, workability, ultrasonic pulse velocity.

1. Introduction

Concrete is a mixture of binder materials, fine aggregate, coarse aggregate, water, and admixtures. Therefore, properties of concrete are strongly depended on the ingredients of concrete and their quality. In which, the coarse aggregate is an important factor, especially the coarse aggregate size (CAS). Thus, ACI 211.1-91 [1] selects the mix proportions of concrete based on the maximum CAS. However, the findings from previous studies regarding the effect of CAS on properties of concrete had a large difference. Some researchers concluded that the compressive strength of concrete increased with reducing the CAS [2]–[7], while the others reported that the compressive strength of concrete increased with increasing the CAS [8], [9]. Furthermore, Rathish and Krishna [10] indicated that concrete reached the highest compressive strength with the use of optimal CAS. This finding was found based on the investigation of concrete made with the CAS of 8 mm, 12.5 mm, 16 mm, and 20 mm. The optimal CAS found in the study was 12.5 mm. On the other hand, some studies showed that workability of concrete reduced when the CAS decreased [2], [4], [7], whereas Rathish and Krishna's experimental work exhibited that the workability of concrete increased with decreasing the CAS [10]. All previous studies related to CAS were conducted in normal condition. The effect of CAS on the properties of concrete fully immersed in sulfate solution is still unknown. Thus, the primary objective of the present study is to investigate the performance of concrete made with different

CAS under sulfate solution. The reduction in compressive strength of concrete immersed in sulfate solution compared with that of concrete cured in water was also evaluated.

2. Materials and Experimental Works

2.1. Materials Properties and Mixture Proportions

Binder materials used in this study were cement and fly ash that provided by local companies in Thanh Hoa province, Vietnam. The cement used was Nghi Son type-PC40 with a specific gravity of 3.12. The fly ash used was classified as class-F with a specific gravity of 2.16. The chemical compositions of cement and fly ash are shown in Table 1. The natural river sand with fineness modulus of 2.87, density of 2.62 T/m³, dry rodded weight of 1.50 T/m³, moisture content of 4.35%, and water absorption capacity of 1.08% was used as fine aggregate. Crushed stone with density of 2.69 T/m³, dry rodded weight of 1.39 T/m³, moisture content of 0.25%, and water absorption capacity of 0.08% was used as coarse aggregate. The superplasticizer with a specific gravity of 1.15 was used with a dosage of 1% by total amount of binder materials.

All concrete mixtures were designed in compliance with ACI 211.1-91 [1] as shown in Table 2. Two group mixtures were designed with water-to-binder ratios of 0.35 and 0.45, referred to M35 and M45, respectively. Each group consisted of four mixtures, which were made with different maximum CASs of 9.5 mm, 12.5 mm, 19 mm, and 25 mm.

Table 1. Chemical Compositions of Cement and Fly Ash

Compositions (wt. %)	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	K ₂ O	Na ₂ O	Others	Loss on ignition (%)
Cement	22.4	5.3	4.0	55.9	2.8	2.1	0.8	0.3	4.5	1.9
Fly ash	48.4	20.4	4.8	2.8	1.4	0.2	1.1	0.8	4.3	15.8

Table 2. Mix Proportions for the Preparation of Concrete Samples

Group	w/b	Concrete ingredients proportion (kg/m ³)					
		Cement	Fly ash	Sand	Stone	Water	SP
M35	0.35	469.1	52.1	811.6	898.4	172.2	5.2
M45	0.45	365.4	40.6	910.3	899.7	178.7	4.1

2.2. Samples preparation and test methods

Workability and fresh unit weight of all mixtures were measured right after mixing. Then, concrete samples were prepared in cylinders with a diameter of 10 cm and a height of 20 cm. After one day, all samples were de-molded and fully immersed in 5% Na₂SO₄ solution until the testing days. The compressive strength and ultrasonic pulse velocity tests were conducted at 3, 7, 14, 28, 56, and 91 days. The average value of three concrete samples at each testing age was reported.

3. Results and Discussion

3.1. Properties of Fresh Concrete

Table 3 shows the slump and fresh unit weight of all concrete mixtures. Concretes made with D_{max} of 9.5 mm and 12.5 mm showed a slightly higher unit weight than two others made with D_{max} of 19 mm and 25 mm. It may be due to the arrangement of coarse aggregate particles inner concrete structure. The large coarse aggregate particles easily create larger pores than the small coarse aggregate particles. These large pores are more difficult to fully fill by paste. However, the difference of unit weight between the concrete mixtures is insignificant.

The slump of the concrete mixture increased with increasing D_{max} of coarse aggregate. This finding is similar to previous studies [2], [4], [7]. The larger CAS is associated with less surface area [11] and thus required less amount of water for wetting and of paste for lubricating the surface of coarse aggregates. For

the same quantity of water, the amount of water on the surface of large CAS is more than that on the surface of small CAS, thus increasing the workability of concrete.

Table 3. Properties of Fresh Concrete Mixtures

Mixture ID.	w/b	SP dosage (kg/m ³)	FA content (%)	Slump (mm)	Fresh unit weight (kg/m ³)
35-9.5	0.35	5.2	10	16	2523
M35-12.5				36	2523
M35-19				55	2513
M35-25				61	2517
M45-9.5	0.45	4.1	10	39	2514
M45-12.5				45	2513
M45-19				87	2493
M45-25				112	2495

3.2. Compressive Strength Development

Figs. 1(a) and 1(b) show the compressive strength development of the M35 and M45 mixtures, respectively. All of the concrete mixtures exhibited an increase of compressive strength during the time. The M35 mixtures had a higher compressive strength than the corresponding M45 mixtures. It is due to the water-to-binder ratio of M35 mixtures is lower than that of M45 mixtures. From Fig. 1, concrete samples made with D_{\max} of 12.5 mm showed the highest compressive strength, followed by concrete samples made with D_{\max} of 9.5 mm, 19 mm, and then 25 mm. This finding is similar to Rathish and Krishna's experimental result [10]. It means that the compressive strength of concrete reached the highest value with the use of optimal CAS. In this case, optimal D_{\max} is close to 12.5 mm. The compressive strength of concrete made with D_{\max} of 25 mm was lowest. Hence, concrete made with larger CAS had lower compressive strength than concrete made with smaller CAS. However, the concrete made with D_{\max} of 12.5 mm showed a higher compressive strength than concrete made with D_{\max} of 9.5 mm. It is attributable to the bond between coarse aggregates. For coarse aggregate with D_{\max} of 9.5 mm, the particle sizes are small; therefore, the interlocking and bond among coarse aggregates is weaker than coarse aggregate with D_{\max} of 12.5 mm. This finding indicated that CAS strongly affects the compressive strength of concrete both under normal condition and sulfate attack condition. It is related to internal bleeding, the development of microcracks, and bonds among coarse aggregate particles [11].

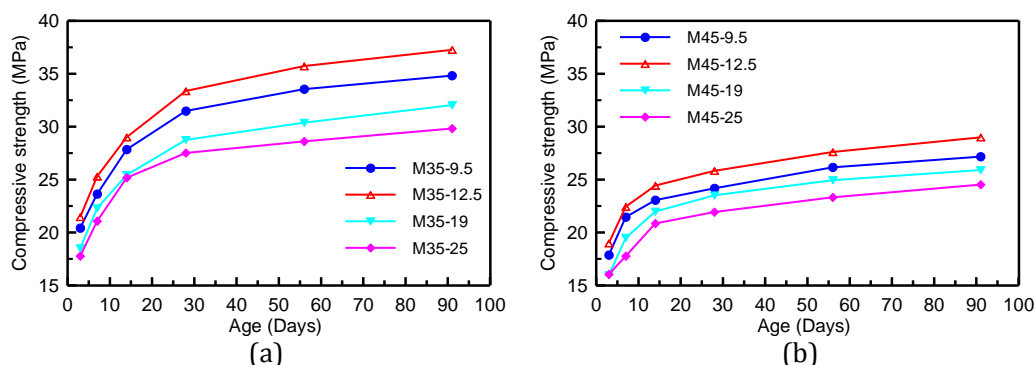


Fig. 1. Compressive strength development of (a) M35 mixtures and (b) M45 mixtures.

3.3. Relative Compressive Strength

Fig. 2 shows the ratio of the compressive strength of concrete fully immersed in sulfate solution and concrete cured in water. For the M35 group, all concrete mixtures showed a similar reduction rate. For the M45 group, concrete made with D_{\max} of 12.5 mm exhibited the least reduction in compressive strength,

followed by concrete made with D_{\max} of 9.5 mm, 19 mm, and then 25 mm. At early state, concrete under sulfate solution had a little higher compressive strength than that under water. It is attributable to the formation of ettringite and gypsum, leading to a denser concrete structure. However, the 91-day compressive strength of concrete in sulfate solution reduced around 8–13% compared with that of concrete cured in water. This result is related to the expansion of ettringite and gypsum at long-term causes the formation of micro-cracks inside the concrete, leading to a reduction in concrete strength.

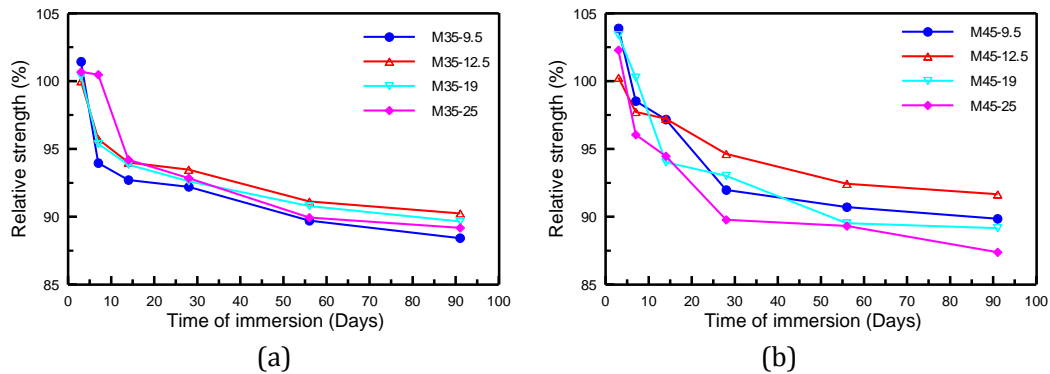


Fig. 2. Relative compressive strength of (a) M35 mixtures and (b) M45 mixtures under sulfate solution and water curing.

3.4. Ultrasonic Pulse Velocity

To assess the durability of concrete, the ultrasonic pulse velocity (UPV) was conducted with the test results are presented in Fig. 3. Generally, the M35 mixtures had higher UPV values than that of the corresponding M45 mixtures. It is due to the low water-to-binder ratio of M35 mixtures compared with M45 mixtures. In both groups, concretes made with D_{\max} of 12.5 mm showed the highest UPV values, followed by concretes made with D_{\max} of 9.5 mm, 19 mm, and 25 mm. This finding is in good agreement with a compressive strength of concrete. It also reflects the presence of voids, cracks, and density inner concrete structure. It also means that the CAS has a significant effect on the durable properties of concrete. However, all concrete samples prepared in this study had a UPV value of greater than 4200 m/s, which was classified as very good quality [12].

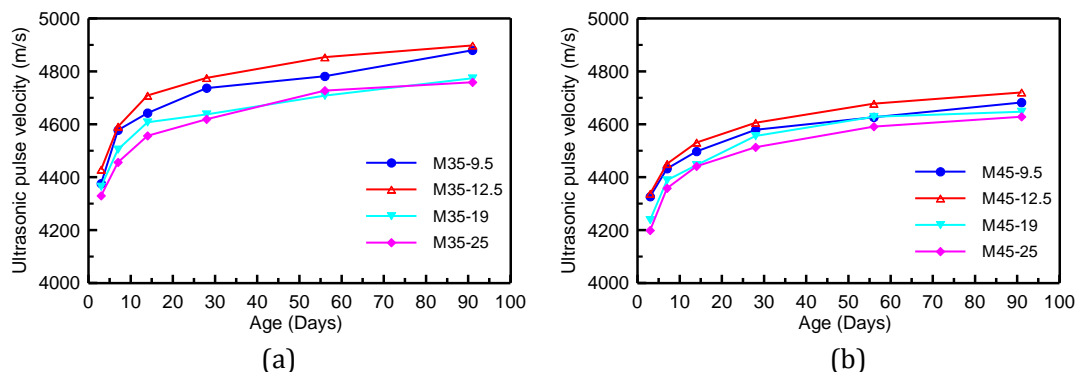


Fig. 3. UPV values of (a) M35 mixtures and (b) M45 mixtures.

4. Conclusions

This study investigates the performance of concrete produced using different CAS and fully immersed in 5% Na_2SO_4 solution. Some major findings of the study are summarized as follows:

1. The workability of fresh concrete increased with increasing the maximum CAS.
2. Concrete made with D_{\max} of 12.5 mm showed the highest compressive strength, followed by concrete made with D_{\max} of 9.5 mm, 19 mm and 25 mm.
3. After 91 days of fully immersing in sulfate solution, the compressive strength of concrete samples reduced around 8–13% as compared with concrete samples cured in water.
4. All of the concrete samples prepared for this study showed the very good quality with the UPV values of all above 4200 m/s.
5. The CAS had a strong effect on the properties of concrete under sulfate solution rather than of the concrete cured in water.

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Trong-Phuoc Huynh is currently a lecturer of the Department of Rural Technology, College of Rural Development, Can Tho University, Can Tho City, Vietnam. He received his MSc. (2013) and Ph.D. degrees (2016) in Civil and Construction Engineering from National Taiwan University of Science and Technology, Taipei City, Taiwan. His research interests are in concrete science and technology, green construction materials, alkali-activated materials, controlled-low strength material, application of pozzolanic materials, and turning wastes into construction materials.