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Characterizing Concrete Performance Mixed with Coarse Aggregate Sourced from Northern Saudi Arabia: A Case Study

Nasser Alanazi[1]
[1]Civil Engineering Department, College of Engineering, University of Ha'il, Ha'il 55474, Saudi Arabia
n.alanazi@uoh.edu.sa

Abstract **-** The coarse aggregate particles, which are a main ingredient in concrete, are typically obtained from crushed rocks or natural deposits such as riverbeds or valleys. This research aimed to explore the effectiveness of using local crushed aggregate as well as local valley aggregate as coarse aggregate in producing concrete. Several standard tests were conducted to explore the physical properties of both aggregate types, and a large number of concrete samples were prepared to test the properties of concrete made with crushed or valley aggregates.

The finding revealed that the crushed aggregate exhibits higher bulk density, specific gravity, and lower water absorption compared to the valley aggregate. Additionally, the workability of fresh concrete made with valley aggregate was better than that of concrete mixed with crushed aggregate, due to the roundness and smoothness of the valley aggregate. However, concrete containing crushed aggregate exhibited better compressive and split tensile strength due to the naturally rough surface and shape angularity. Finally, the study concluded that both sources of coarse aggregate are suitable for use in concrete production, with concrete incorporating crushed aggregate slightly stronger and concrete made with valley aggregate having better workability.

Keywords**:** coarse aggregate, concrete mix design, workability, compressive strength

1. Introduction

Concrete is the most widely used construction material around the world, where approximately 25 billion tons of concrete are produced annually [1], which is equivalent to 3.8 tons per person each year [2]. This massive consumption of concrete is because of its cost-effectiveness, local availability, strength, and durability [3& 4].

Hydrated concrete consists of three components: aggregate, cement paste, and the interfacial transition zone (ITZ) [3& 4]. The ITZ is the contact area between the cement paste and the aggregate particles [4& 5]. Aggregate particles account for around 70% to 80% of the total concrete volume [3], with coarse aggregate (larger than 4.75 mm sieve) comprising around 40% to 50% [6]. Conventionally, crushed rocks and naturally available aggregate are used as a source of coarse and fine aggregate (smaller than 4.75 mm sieve) in concrete production [4].

The strength of concrete is directly influenced by the characteristics of the cement paste, the strength of the aggregate, and the ITZ [3& 4, 7]. In normal-strength concrete, the ITZ is the weakest link in the chain, which controls the overall strength of concrete because of micro-cracks initiation within the ITZ, and then those micro-cracks collide and propagate through the cement paste [7]. This concrete failure mechanism commonly happens in normal concrete except for lightweight aggregate and expanded clay aggregate [7].

Generally, angular aggregate with rough surface texture (i.e., crushed rocks) enhances the strength of the ITZ, in contrast to smooth surface texture and rounded aggregate (i.e., river aggregates), which weakens the ITZ [4, 7]. For high-strength concrete, which is achieved by lowering the water-to-cement ratio, the strength of the used coarse aggregate plays a crucial role because the ITZ bonding strength could reach a level comparable to the strength of the coarse aggregate itself, making the use of high-strength aggregate with suitable surface texture and shape is essential when designing high-strength concrete greater than 40 MPa [8].

The current study investigates the suitability of using locally available crushed aggregate (CA) and valley aggregate (VA) from the northern regions of Saudi Arabia as coarse aggregate particles in concrete production. The characterization process will begin by examining the physical properties of both the CA and the VA. Subsequently, the performance of concrete samples containing these aggregates will be assessed. Specifically, the workability of fresh concrete and the mechanical properties of hardened concrete, including compressive strength and split tensile strength, will be evaluated for concrete mixes containing both the CA and the VA.

2. Experimental works

The experimental work, from preparing the concrete specimens to performing the fresh and hardened concrete tests and generating the experimental results, was performed at the material and structural laboratory at the University of Hail, Hail, Kingdom of Saudi Arabia. The preparation of concrete patches was carried out in the material laboratory under controlled humidity and temperature conditions. The mixing process began by weighing the ingredients according to the desired mix design. Then, all the weighed ingredients, except for water, were added to a drum-tilted mixer (dry mixing method) [9]. The mixer was operated for 1 to 2 minutes to ensure a thorough blending until a uniform color and texture were achieved. Next, the water was slowly added while the mixer was running. Finally, the mixer continued running for an additional 2 to 3 minutes until the concrete batch reached a consistent and uniform texture.

2.1. Material used

The raw materials used in this experimental research were ordinary Portland cement, fine aggregates, CA and VA as coarse aggregates, and water. The cement used was the general-purpose Portland cement [CEM I 42.5 N] produced locally in the northern regions of Saudi Arabia, and it complies with ASTM C150 [10]. Fine aggregate was dune sand supplied locally to the material lab at the University of Hail. In this study, the CA was provided by a local quarry supplier, whereas the VA was collected from valley beds around the Hail region. In this research, tap water was used, which is safe for drinking and free from harmful impurities as specified in ASTM C94 [11].

2.2. Physical properties of coarse aggregate

The aggregate particle distribution of both the CA and the VA was determined using the sieving analysis procedure according to the standard method prescribed by ASTM C136 [12]. The CA and the VA aggregate size distributions are shown in Fig. 1. According to Fig.1, the nominal maximum size of both CA and VA aggregates is 12.5 mm. Also, both coarse aggregate gradation curves fall between the upper and lower limit curves provided by the standard.

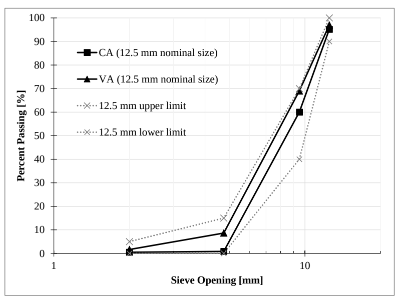


Fig.1: aggregate size distribution of the coarse aggregate used in this study.

The loose and compacted bulk densities of the CA and the VA were determined according to the standardized procedure found in ASTM C29 [13]. It was found that the bulk density (loose state condition and oven-dry basis) of the VA was 1303 kg/m^3, whereas the bulk density (loose state condition and oven-dry basis) of the CA was 1419 kg/m^3. The bulk densities (compacted state condition and oven dry bases) were 1419 kg/m^3 and 1494 kg/m^3 for the VA and the CA, respectively. From those results, it was concluded that the loose and compacted bulk densities of the VA were 8.2% and 5% lower compared to the CA loose and compacted bulk densities, respectively. Based on Saturated-Surface Dry (SSD) conditions, the loose and compacted bulk density values were found equal to 1339 kg/m^3 and 1458 kg/m^3 for the VA, respectively. On the other hand, the loose and compacted bulk density values for the CA were 1463 kg/m^3 and 1540 kg/m^3, respectively. In spite of the significant differences in the bulk density values, both the CA and the VA could be classified as normal-weight aggregates because the values of the densities are in the range of 1280 kg/m^3 to 1920 kg/m^3 [14].

The VA and the CA water absorption capacity were calculated according to ASTM C127 [15]. It was found that the water absorption value of the VA was 2.54%, whereas the water absorption value of the CA was 2.50%. The water absorption results indicate that the VA coarse aggregate is slightly more porous than the CA, which means the VA absorbs marginally more water than the CA under the same circumstances.

The VA and the CA specific gravity values were determined following the ASTM C127 [15]. The values for oven-dry, dry, Saturated-Surface-Dry (SSD), and apparent conditions for the VA were 2.43, 2.50, and 2.60, respectively. In comparison, the specific gravity values based on oven-dry, SSD, and apparent conditions for the CA were found to be equal equal to 2.54, 2.61, and 2.71, respectively.

2.3. Concrete Mix Designs

In this study, two concrete mix design groups were prepared. The first group had a w/c ratio equal to 0.45, while the second group had a w/c ratio equal to 0.35. Each group was divided into two sets. The first set involved manufacturing concrete specimens with the CA, while the second set involved preparing concrete specimens with 100% replacement by volume of the CA by the VA. It is worth highlighting here that the aggregate full replacement was based on SSD conditions to ensure that the aggregate absorption of water during the mixing process is prevented. The concrete mix proportions are presented in Table 1. Concrete cylinders having a diameter of 150 mm and a length of 300 mm were fabricated from each concrete mix design and stored in a curing tank for curing periods of 7, 14, and 28 days at a constant temperature of 25 °C. On the day before fabricating the concrete specimens, the coarse aggregate particles were submerged in water for 24 hours, and then they were given enough time for the surface moisture to evaporate (SSD condition) before weighing them.

Table 1: Concrete mix proportions by weight

Concrete Mix ID	**Cement**	**Crushed aggregate (CA)**	**Valley Aggregate (VA)**	**Sand**	**Water**	**Superplasticizer**
CA 1	1	2.1	-	1.55	0.45	-
VA 1	1	-	2.02	1.55	0.45	-
CA 2	1	2.1	-	1.55	0.35	1.3% of cement
VA 2	1	-	2.02	1.55	0.35	1.3% of cement

3. Results and discussion

3.1 Workability

Although there is no universally accepted standard test to measure concrete workability [3, 7], fresh concrete workability could be measured using the slump test according to ASTM C143 [16] and according to the inverted cone flow table test by following the steps outlined in ASTM C1611 [17]. The workability of concrete mixes with the w/c ratio equal to 0.45 was measured using the slump test, while the workability of concrete mixes with the w/c ratio of 0.35 was measured using the inverted slump cone test.

The slump value of the CA1 mix was 85 mm, but the value for the VA1 mix was 105 mm. The flow table diameter of the CA2 mix was 560 mm, however, the value of the VA2 mix was 580 mm. The results indicate that, for concrete mixes with the natural valley aggregate, the slump value increased by 23.5% compared to the CA1 concrete mix. And the flow table diameter also increased by only 3.6 % for the VA2. The roundness and shape of the valley aggregate significantly impact the fresh concrete workability, which is demonstrated by a 23.5% increase in the slump value compared to the concrete mix containing crushed aggregate particles. This result indicates that the slump test is primarily affected by the shape and surface texture of the aggregate particles. To this end, VA aggregate particles contribute to the consistency and workability of the concrete mixes compared to the performance of the CA aggregate particles.

On the other hand, the inverted-cone flow table test is less sensitive to the aggregate roundness and surface texture. The roundness of VA aggregate particles marginally increased the flow table diameter by only 3.6%. This is attributed to the nature of the flow table test because concrete spreads as one mass. Therefore, factors such as the consistency of the mix proportions and the amount of cement lubricating the aggregate particle are primary factors that determine the entire mix performance in this test.

4. Hardened concrete properties
4.1 Compressive strength

The compressive strength of concrete is one of the most important properties because it directly measures the material's ability to sustain the structural loads. The compressive strength is obtained by testing concrete cubes or cylinders according to the ASTM C39 [18], where an axial load is applied to the specimen until failure. The maximum force is recorded and divided by the cross-sectional area of the tested cylinder to determine the compressive strength.

In order to evaluate the compressive strength, 150 mm by 300 mm concrete cylinders were prepared using the different mix designs presented in Table 1. All the experimental results generated from testing the concrete cylinders under compression are plotted in Figs. 2& 3.

Fig. 2 presents the compressive strength of cylinders manufactured from CA1 and VA1 mix designs. From the figure, it is clear that the CA1 mix design has higher compressive strength than VA1 at the 7, 14, and 28 days of curing. This result is expected because the CA shape angularity and rough surfaces provide better bonding between the aggregate and cement paste (the ITZ strength).

Fig. 3 shows the compressive strength generated from testing concrete cylinders fabricated from CA2 and VA2 concrete mix designs. The results show improvement in the compressive strength of both mix designs due to lowering the water-cement ratio to 0.35. Furthermore, as discussed earlier, the crushed aggregate consistently demonstrates better compressive strength.

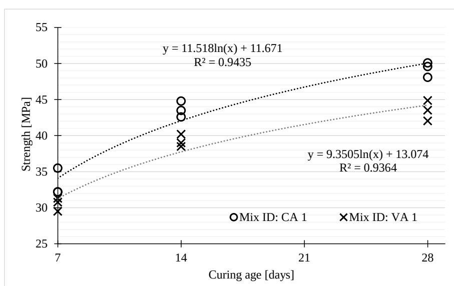


Fig. 2: Compressive strength versus curing days of concrete made with crushed aggregate (CA1) and valley aggregate (VA1), with a w/c ratio of 0.45.

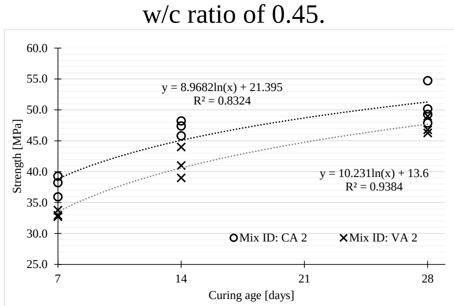


Fig.3: Compressive strength versus curing days of concrete made with crushed aggregate (CA1) and valley aggregate (VA1), with a w/c ratio of 0.35.

4.2 Tensile Strength

In this study, the tensile strength was determined according to ASTM C496 [19]. The test involves applying a diametral compressive load along the length of the specimen until failure. Figures 4 and 5 summarize the split tensile strength of specimens made from all concrete mixes. Specifically, Fig. 4 presents the split tensile strength of CA1 and

VA1 at 7 and 28 curing days. And, Fig. 5 presents the split tensile strength of CA2 and VA2 mix designs at 7 and 28 curing days. Overall, the split tensile strength of concrete mixed with crushed aggregate shows higher tensile strength.

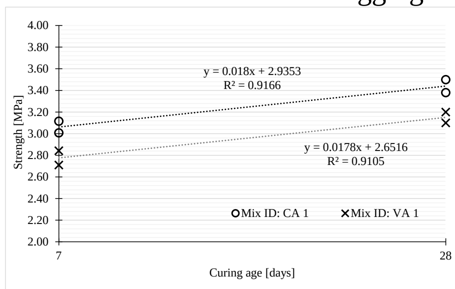


Fig.4: Split tensile strength versus curing days of concrete made with crushed aggregate (CA1) and valley aggregate (VA1), with a w/c ratio of 0.45.

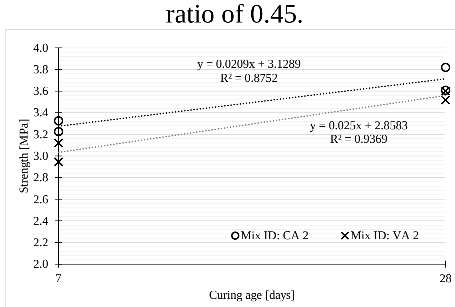


Fig.5: Split tensile strength versus curing days of concrete made with crushed aggregate (CA2) and valley aggregate (VA2), with a w/c ratio of 0.35.

5. Schmidt Rebound Hammer Test and Results

Schmidt hammer is a non-destructive testing method that is commonly used for estimating the compressive strength of concrete [4]. The working principle of the rebound hammer is fairly simple: a spring-loaded mass strikes the concrete surface, and the rebound distance is measured along a guide scale. This rebound index is then correlated with the compressive strength [7].

In this research, the rebound hammer tests were performed following the ASTM C805 [20] standard procedure. The standard requires that the concrete surface be clean and free from moisture prior to testing. Therefore, the test specimens were kept in an air-dry condition for 24 to 48 hours before conducting the test. A minimum of 10 rebound readings were taken on two specimens, and then all the readings were averaged.

According to the literature, numerous investigators have explored the relationship between the rebound index and the destructive compressive strength. As a result, many models were developed, including polynomial [21], linear [22], and power [22& 23] models. For the current investigation, after carefully investigating the literature, two power models were considered in this study, which are as follows:

$f_{CR} = 0.0152R^{2.119}\ [MPa]$ Antonio et al. [24] (Equation 1)

$f_{CR} = 0.0501R^{1.8428}\ [MPa]$ Lima and Silva [23] (Equation 2)

Where f_{CR} is the predicted compressive strength of concrete and R is the rebound hammer index. Table 2 summarizes all the averaged rebound readings, the average destructive compressive strength, the predicted compressive strength, and the percent error calculated according to the following :

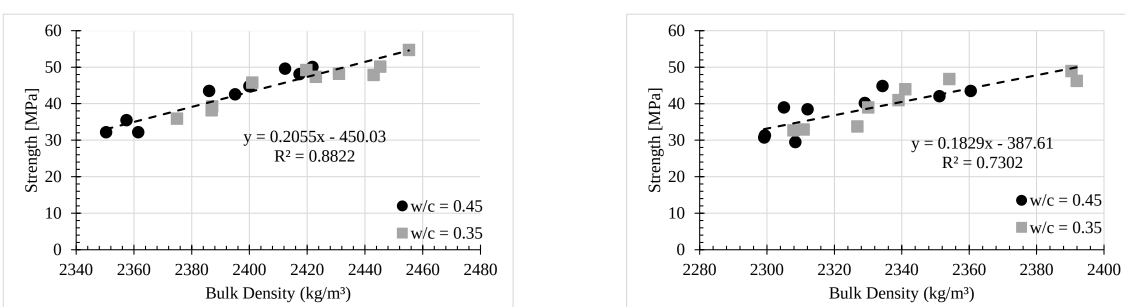
$Error = \frac{f_c' - f_{CR}}{f_c'}$ (Equation 3) where f'_c is the destructive compressive strength. As shown in Table 2, the error scattering from both models was generally within ±20%.

Table 2: Accuracy of the models used to estimate the compressive strength of all concrete mixes at different curing ages.

				Equation 1		Equation 2	
Mix ID	curing Days	f'_c [MPa]	Average Rebound hammer index (R)	f_{CR} [MPa]	% error	f_{CR} [MPa]	% error
CA 1	7	33.3	32	30.99	6.94	29.75	10.65
	14	43.6	40.6	45.61	-4.60	46.13	-5.81
	28	49.2	39.5	43.62	11.34	43.86	10.86
CA 2	7	37.8	40	44.52	-17.77	44.89	-18.75
	14	47.13	41	46.34	1.68	46.98	0.33
	28	50.5	41.8	47.82	5.31	48.68	3.61
VA 1	7	30.5	32	30.99	-1.60	29.75	2.45
	14	39.2	35.5	36.68	6.44	36.02	8.10
	28	43.5	38.1	41.14	5.43	41.04	5.66
VA 2	7	33.1	40	44.52	-34.50	44.89	-35.61
	14	41.3	42.27	48.69	-17.90	49.69	-20.32
	28	47.3	42.833	49.75	-5.18	50.92	-7.65

6. Concrete Bulk density and compressive strength

From the experimental work conducted in this investigation, a relationship between the bulk density of concrete and the compressive strength was derived, as shown in Fig. 6. The figure demonstrates that there is a strong correlation between the compressive strength and the bulk density with a value of the coefficient of determination, R2, of 0.88 for concrete mixed with crushed aggregate (Fig.6a) and 0.73 for concrete mixed with valley-bed aggregate (Fig.6b). However, more experimental work is needed to establish a more accurate correlation.



(a) (b)

Fig.6: Correlation between concrete bulk density and compressive strength of concrete mixed with crushed aggregate (a) and valley-bed aggregate (b).

7. Conclusion

A large number of concrete cylinders were fabricated with the available local coarse aggregates in northern Saudi Arabia Arabia and then tested to assess the concrete performance. Both local crushed aggregate and valley-bed aggregate could be be used as coarse aggregate in fabricating concrete. The key outcomes of this study are summarized as follows:

- The coarse valley aggregates have relatively lower bulk density, lower specific gravity, and slightly higher water absorption than the coarse crushed aggregates.
- The roundness and smoothness of the valley aggregate increased the workability of concrete compared to the workability of concrete having crushed aggregates.
- Concrete incorporating the valley aggregate showed slightly lower compressive strength compared to the crushed aggregate concrete.
- Suitable empirical relationships between the rebound hammer and the compressive strength were extrapolated from the literature and used to predict the strength of concrete made locally in the north of Saudi Arabia.
- A direct relationship between concrete bulk density and the compressive strength of concrete was derived. However, further research studies should be conducted with various concrete mix designs to better understand their correlation.

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