

# Shear behavior of concrete deep beams with single coarse aggregate sizes

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## Abstract

Deep beams are structural members characterized by a large depth-to-span ratio, where their strength is primarily governed by shear rather than flexure. Shear behavior depends significantly on the concrete composition and reinforcement arrangement, which is typically denser in deep beams due to their geometry and stress distribution. This study presents a practical investigation into the behavior of reinforced concrete deep beams cast using concrete with a single size of coarse aggregate—an uncommon approach since most design references recommend graded aggregates to prevent segregation and ensure uniform strength. 15 reinforced concrete deep beams were cast and tested under two-point loading. The specimens were divided into three groups based on the coarse aggregate size and shear span-to-effective depth ratio ( $a/d$ ). The experimental results revealed that beams with 20 mm and 25 mm coarse aggregates exhibited superior performance compared to those with 15 mm and 37.5 mm aggregates. The findings indicate that the shear strength of deep beams is influenced by the size of coarse aggregate and the  $a/d$  ratio, with both factors interacting to affect the overall shear behavior. This research highlights the feasibility and implications of using single-size coarse aggregate in deep beam construction.

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**Keywords:** Deep beam, Single aggregate size, Shear failure, Strength,  $a/d$  ratio

## 1. Introduction

Deep beams are structural components used in many structural applications, including multistory transfer girders, pile-supported foundations, foundation walls, rectangular tank walls, shear walls, and bridges. Deep beams vary from slender beams in their geometrical dimensions [1].

The ACI 318M-19 Code [2] describes deep beams whenever "members loaded on one face and supported on the opposite face so that compression struts can develop between the loads and the supports." As illustrated in Figure 1, deep beams are described as all those partners with an effective span ( $L_n$ ) to depth ( $h$ ) ratio of less than or equal to four ( $L_n/h \leq 4$ ) or ( $a/h \leq 2$ ) ratio of less than or equal to two; where ( $h$ ) is depth of the partners, ( $a$ ) is shear span is the range between the axis of the support and the closest concentrated load point.

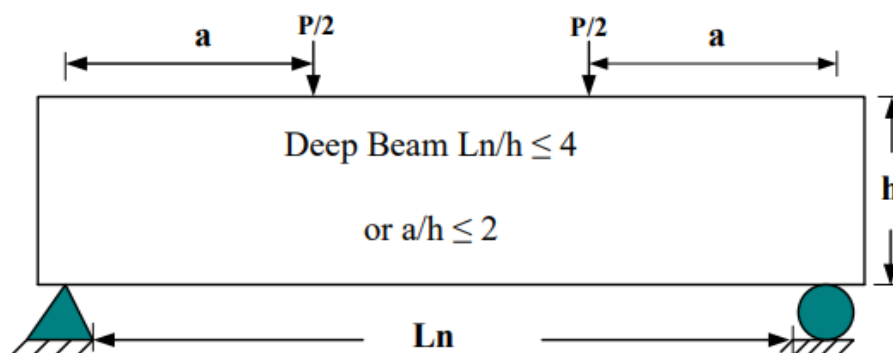


Figure 1. Deep beam limitation

Any set of aggregates contains elements of different sizes. The distribution of the element sizes within the set is called grading or gradation. It is usually expressed as the number of the different-sized elements of particles, as the percentage of the total quantity of the set, or even more frequently as the cumulative percentage of the particles that are smaller (or larger) than the series of sieve openings [3].

One of the most significant properties of aggregate is its particle size distribution, or gradation. Gradation influences practically all significant qualities, such as rigidity, soundness, toughness, permeability, workability, chemical resistance, and frictional resistance to water penetration. Gradation is an important part of mix design [4].

Most authorities specify the permissible aggregate gradations. In the present study, the 15 deep beams that were cast for the experiment were separated into three groups and categorized based on the coarse aggregate size and shear span to effective depth ratio ( $a/d$ ). The effect of coarse aggregate size and the effect of the shear span to effective depth ratio ( $a/d$ ) on the load-mid span deflection, crack pattern, and shear strength of the deep beams containing a single size of coarse aggregate were studied.

One of the main motivations for this research is to investigate the shear behavior of deep beams in the presence of a single coarse aggregate, since shear behavior in general depends on the composition of the concrete and the materials used in it. The reinforcement in deep beams is typically denser than in other structural elements due to their shape, dimensions, and the stresses to which they are subjected.

## 2. Experimental program

15 concrete deep beams, simply supported, that make up the experimental approach, are being tested. The shapes and reinforcement of each beam are similar; a total of 1000 mm in length, 400 mm in height, and 150 mm in width. Every specimen is intended to undergo shear failure (Figure 2). Every one of the tested beams has two layers of 2Ø16mm of flexural bottom reinforcement ( $\rho = 0.0151$  when  $\rho =$  ratio of flexural reinforcement). A web reinforcement complied with the minimum requirements, with 6@100mm of vertical and horizontal. According to the ACI Committee 318M-2019 [2], two equal loads are applied to a specimen, which has been assessed for an actual span equal to 760 mm, leading to a 1.9 ratio of clear span to total depth ( $L_n/h=1.9$ ), which is less than 4.

As shown in Table 1, there were three groups into which the specimens were separated. Categories were made based on the shear span to effective depth ratio  $a/d$ , where group (A) has a 0.6 ratio of  $a/d$ , group (B) has with 0.8 and group (C) has with 1 ratio. Each group includes five beams. The first one is casting with continuous gradient of coarse aggregate 5-20 mm used as reference; the second sample casting with single size 14 mm of coarse aggregate; the third sample casting with single size 20 mm of coarse aggregate, and the fourth sample casting with single size 25 mm of coarse aggregate and the fifth sample casting with single size 37.5 mm of coarse aggregate.

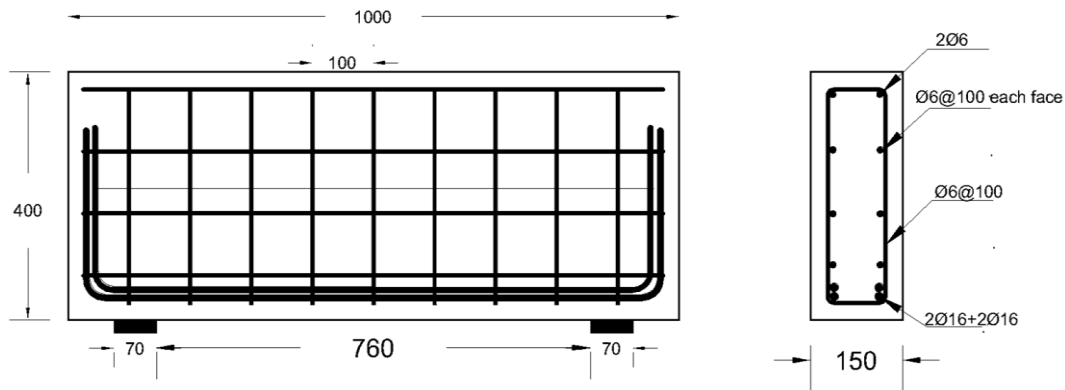


Figure 2. Deep beam specimen details

Table 1. Beam specimen details

Group	Beam Name	Aggregate Size (mm)	a/d Ratio
A	AG-CG-a/d-6	CG	0.6
	AG-14-a/d-6	14	0.6
	AG-20-a/d-6	20	0.6
	AG-25-a/d-6	25	0.6
	AG-37.5-a/d-6	37.5	0.6
B	AG-CG-a/d-8	CG	0.8
	AG-14-a/d-8	14	0.8
	AG-20-a/d-8	20	0.8
	AG-25-a/d-8	25	0.8
	AG-37.5-a/d-8	37.5	0.8
C	AG-CG-a/d-1	CG	1
	AG-14-a/d-1	14	1
	AG-20-a/d-1	20	1
	AG-25-a/d-1	25	1
	AG-37.5-a/d-1	37.5	1

## 2.1. Materials

The current work, Portland cement with type-I from the Karbala manufacturing site, was utilized. The physical characteristics as well as chemical makeup of the used cement are shown in Tables 2 and 3, respectively. The test results meet ASTM (2019), Standard Specification for Portland cement in ASTM C150/C150M19a requirements [5].

The Al-Ukhaidher location provided natural sand with a 2.85 of fineness modulus. Table 4 displays the fine aggregate's grading (3-4). Physical properties were displayed in Table 5. Data showed the content of sulfate and the grading in fine aggregate, which was in accordance with Standard Specification for Concrete Aggregates [6].

Crushed gravel was divided into five groups. One group had a continuous grading with a maximum size of 20 mm (see Table 6). The other four groups consisted of single-size coarse aggregates of 37.5 mm, 25 mm, 20 mm, and 14 mm, respectively. These aggregates were extracted from the Al-Niba'e area and processed at the Construction Materials Laboratory in the College of Engineering, Mustansiriyah University, as shown in Figure 2. The physical properties of the aggregates are presented in Tables 3 to 7. The results indicated that the grading and characteristics of the coarse aggregates complied with Iraq's Specification No. 45/1984 [6].

Table 2. Cement's physical characteristics

Characteristics	Test findings	Iraqi Specification No.5/1984 Limit
Fineness using the Blaine air permeability apparatus ( $m^2/Kg$ )	311	> 230
Soundness by the autoclave method	0.17 %	< 0.8%
Setting time by Vicat's apparatus		
Initial (min)	155	> 45
Final (hr)	4.23	< 10
Compressive strength (MPa) for a 70.7mm cube of cement paste		
3 days	28.7	>15
7 days	32.4	> 23

Table 3. Chemistry and the main components of cement

Compound Composition	Chemical Composition	Percentage By Weight %	Limit of Iraqi Specification No.5/1984
Lime	CaO	63.45	-
Silica	SiO <sub>2</sub>	19.4	-
Alumina	Al <sub>2</sub> O <sub>3</sub>	5.41	-
Iron oxide	Fe <sub>2</sub> O <sub>3</sub>	2.76	-
Magnesia	MgO	2.5	< 5.0
Sulfate	SO <sub>3</sub>	2.12	< 2.8
Loss on ignition	L.O.I.	3.21	< 4.0
Insoluble residue	I.R.	0.76	< 1.5
Lime saturation factor	L.S.F.	0.80	(0.66-1.02) %
Bogue's Equation-Main Compounds			
Tricalcium Silicate	C <sub>3</sub> S	57.12	-
Dicalcium Silicate	C <sub>2</sub> S	16.22	-
Tricalcium Aluminate	C <sub>3</sub> A	3.30	-
Tetra calcium alumino ferrite	C <sub>4</sub> AF	13.25	-

Table 4. A Fine aggregate's grade

Sieve Size (mm)	% Passing	
	Fine Aggregate %	Limit of Iraqi Specification No. 45/1984 for Zone 2
4.75	90.56	90-100
2.36	74.69	75-100
1.18	60.44	55-90
0.60	43.47	35-59
0.30	13.72	8-30
0.15	1.98	0-10

Table 5. Characteristics of fine aggregate

Physical Properties	Test Results	Limit of Iraqi Specification No. 45/1984
Specific Gravity	2.56	—
Sulfate Content	0.09 %	< 0.5 %
Absorption	0.73 %	—

Table 6. A coarse aggregate's grade

Sieve Size (mm)	Passing Percentage	
	Coarse Aggregate (%)	Limit of Iraqi Specification No. 45/1984
37.5	100	100
20	96.24	95-100
14	46.64	----
10	34.80	30-60
5	5.20	0-10
2.36	4.72	----

Table 7. Coarse aggregate characteristics

Physical Properties	Test Results	Limit of Iraqi Specification No. 45/1984
Specific Gravity	2.6	-----
Sulfate Content	0.06%	< 0.1%
Absorption	0.75%	-----



(a) only 37.5 mm



(b) only 25mm



(c) only 20mm



(d) only 14mm

Figure 2. Sizes of coarse aggregate used

## 2.2. Steel reinforcement

Two layers of nominally 2 $\phi$ 16mm steel bars with deformed surface were employed in longitudinal reinforcement, also  $\phi$ 6 mm was also used in the web zone. Testing on steel reinforcement was conducted, according to ASTM c370-05a [7]. To ascertain the mean yield stress and the ultimate stress, the test was conducted utilizing the test equipment offered by the construction materials laboratory in the College of Engineering / Mustansiriyah University. Figure 3 depicts the steel reinforcing cage used in deep beams. The test results are listed in Table 8.

Table 8. Steel reinforcing bar characteristics

Nominal Bar Diameter (mm)	Measured Bar Diameter (mm)	Bar Area (mm <sup>2</sup> )	Yield Stress (MPa)	Ultimate Stress (MPa)
16	16	201.6	522	661
6	6.1	28.27	480	550



Figure 3. Steel reinforcement cage used in deep beams

## 2.3. Concrete mix design

Normal-strength concrete mixes were made with a nominal 28-day compressive strength of 32MPa. Mix details are given in Table 9, which was achieved by adopting the mixing ratios proposed by previous research by Mahdi [8].

Table 9. Concrete mix proportions per cubic meter

Compressive Strength (MPa)	Cement (kg/m <sup>3</sup> )	Sand (kg/m <sup>3</sup> )	Gravel (kg/m <sup>3</sup> )	Water Cement ratio w/c
32	400	600	1200	0.45

## 2.4. Test procedure

At the age of 28 days, all beam samples and control samples were taken out of the curing process. The beam samples were cleaned and painted white before the testing day to help visualize the fracture growth. Each beam sample has labels on it. The locations of the supports, loading marks, as well as the dial gauge position have all been marked on the surface of the beam. Two steel plates with the dimensions (150x70x40) mm (length, width, depth) have been placed over the support points and under the load points to avoid concentrating stress on the beams' top face while loaded. With a 760mm clear span, the beam specimens have been put on the apparatus.

Single node loading of the test machinery is placed on the top center of a load-carrying bridge to begin the loading operation. Then, as illustrated in Figure 4, a singular force is split evenly among two 2-point forces that have been supplied with the beam specimen via dual shafts linked to bridges. Loading was applied in 10 kN increments. The deflection measurements at the midspan of the beam were taken at each load stage. The load corresponding to the appearance of the first crack was noted. On the surface of the beam, the first and subsequent

fractures' locations and sizes were noted, and the magnitude of the load stage at which they appeared was noted. Up to failure, the loading increments were used.

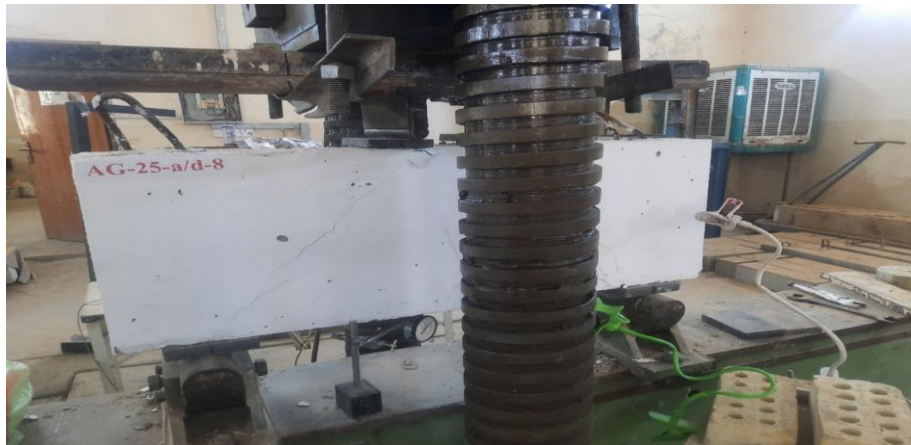


Figure 4. Test setup of deep beams

### 3. Experimental results

In this section, the results of the tested beams and their corresponding behaviors are presented and discussed. Table 10 summarizes the results for the first shear crack ( $v_{cr}$ ) and the ultimate shear strength ( $v_u$ ) for all tested beams, along with their respective modes of failure. The ultimate shear strength is calculated as  $v_u = p_u/2$ . The table also highlights the main variables that distinguish the differences between the tested beams.

Table 10. Test results of a concrete deep beam with a single size of coarse aggregate

Group	Beam Name	Aggregate Size ( $\varnothing$ mm)	a/d Ratio	Visible $V_{cr}$ (kN)	$V_n$ (kN)	$V_{cr}$ / $V_n$	$\Delta_f$ (mm)
A	AG-CG-a/d-6	CG	0.6	87.5	292.5	30%	1.72
	AG-14-a/d-6	14	0.6	82.5	282.5	29%	2.55
	AG-20-a/d-6	20	0.6	112.5	347.5	32%	2.28
	AG-25-a/d-6	25	0.6	120	390	31%	2.34
	AG-37.5-a/d-6	37.5	0.6	100	335	30%	2.4
B	AG-CG-a/d-8	CG	0.8	80	282.5	28%	2.2
	AG-14-a/d-8	14	0.8	70	267.5	26%	2.8
	AG-20-a/d-8	20	0.8	95	315	30%	2.5
	AG-25-a/d-8	25	0.8	105	350	30%	2.68
	AG-37.5-a/d-8	37.5	0.8	80	275	29%	2.77
C	AG-CG-a/d-1	CG	1	62.5	247.5	25%	2.32
	AG-14-a/d-1	14	1	55	230	24%	3.18
	AG-20-a/d-1	20	1	67.5	250	27%	2.71
	AG-25-a/d-1	25	1	70	280	25%	2.9
	AG-37.5-a/d-1	37.5	1	65	245	27%	3.01

#### 3.1. Effect of coarse aggregate size

##### 3.1.1. Group (A); a/d=0.6

From the results of Table 11 and Figure 5, it was observed that the first shear crack and shear strength varied with changes in the size of the coarse aggregate used in the samples. Specifically, the first shear crack decreased by 6% for the sample with a 14 mm coarse aggregate size compared to the reference sample with continuous

gradation (AG-CG-a/d-6). In contrast, there was an increase of approximately 29%, 37%, and 14% for samples with coarse aggregate sizes of 20 mm, 25 mm, and 37.5 mm, respectively.

Regarding the shear strength, the value decreased by 3% when the aggregate size in the sample was 14mm, compared to the first sample. Still, the rest of the sizes showed different results and were higher than the reference, where the two samples with coarse aggregate sizes 20mm and 25mm increased by 19% and 33% and by 15% for the sample with coarse aggregate size 37.5mm.

Table 11. Effect size of coarse aggregate on the first shear cracking and shear strength when a/d=0.6

Group	Beam Name	V <sub>cr</sub> (kN)	V <sub>n</sub> (kN)	Δ <sub>f</sub> (mm)	%Changing of Shear Cracking According to (AG-CG-a/d-6)	%Changing of Shear Strength According to (AG-CG-a/d-6)
A	AG-CG-a/d-6	87.5	292.5	1.72	---	---
	AG-14-a/d-6	82.5	282.5	2.55	-6%	-3%
	AG-20-a/d-6	112.5	347.5	2.28	29%	19%
	AG-25-a/d-6	120	390	2.34	37%	33%
	AG-37.5-a/d-6	100	335	2.4	14%	15%

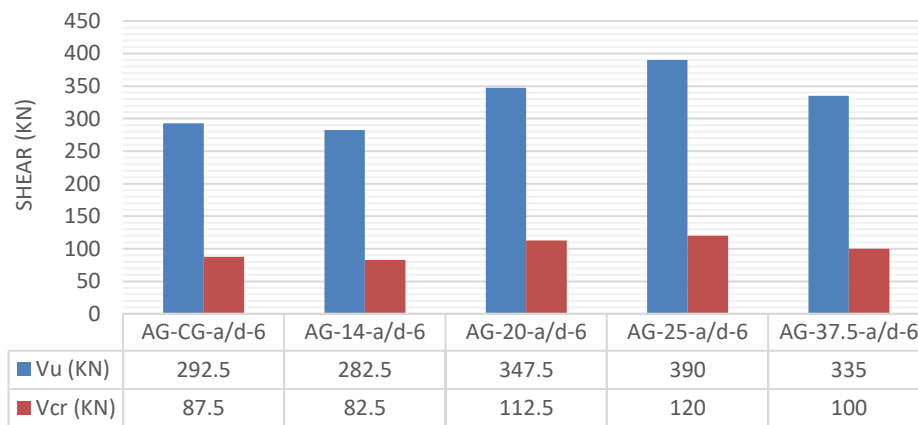


Figure 5. Effect size of coarse aggregate on the first shear cracking and shear strength when a/d = 0.6

All deep beams tested in this group had a diagonal splitting failure mode, where concrete crushing occurred in the compression portion of the web of the deep beam, but there was no significant difference noted in the (AG-37.5-a/d-6) sample when some cracks were obtained above the inclined strut zone and in the gross section side (Figures 6 and 7).

Figure 6. Crack pattern after testing for beam (AG-37.5-a/d-6)



Figure 7. Crack pattern for beam (AG-37.5-a/d-6)

The curves presented in Figures 8 and 9 illustrate how coarse aggregate size affects the load–mid-span deflection of deep beams with a single size of coarse aggregate. It was observed that the deep beam with a continuous gradient (AG-CG-a/d-6) deflected about 1.72 mm. When the aggregate size was increased to 14 mm, the deflection increased to 2.7 mm. However, with further increases in coarse aggregate size to 20 mm and 25 mm, the deflection values slightly decreased compared to the 14 mm case, but remained higher than the reference sample (AG-CG-a/d-6), with deflections of 2.46 mm and 2.5 mm, respectively. For the beam with a 37.5 mm aggregate size, a smaller deflection of 2.18 mm was recorded, considering the ultimate load carried.

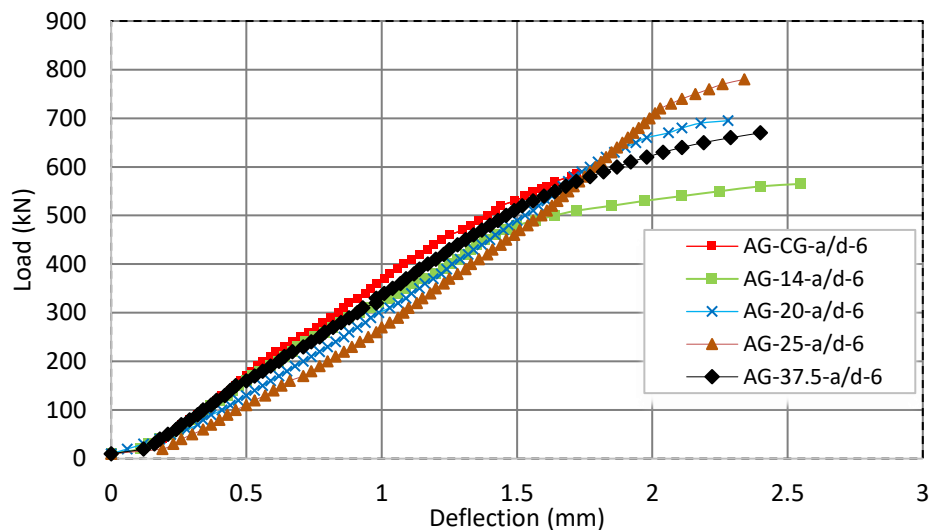


Figure 8. Effect size of coarse aggregate on load mid-span deflection when  $a/d = 0.6$

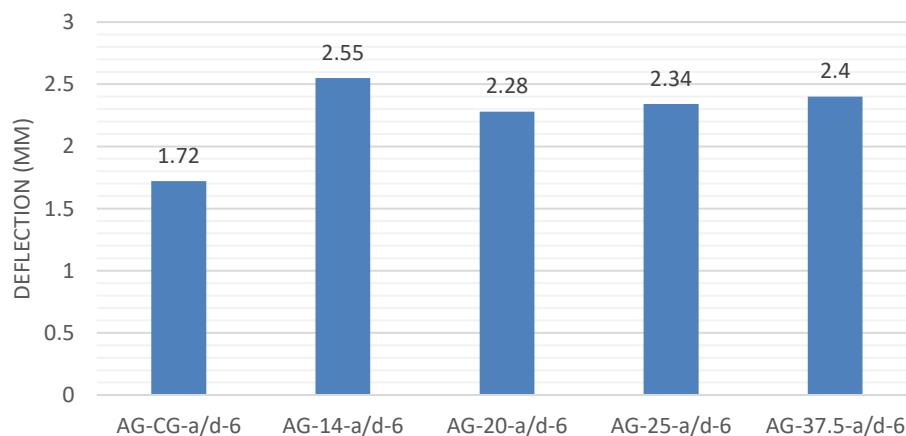


Figure 9. Effect size of coarse aggregate on load mid-span deflection when  $a/d = 0.6$

### 3.1.2. Group (B); a/d=0.8

The effective span ratio (a/d) in this group is equal to 0.8. A decrease of 13% in the appearance of the first shear crack was observed in concrete deep beams with an aggregate size of 14 mm compared to the reference beam. However, in deep beams with aggregate sizes of 20 mm and 25 mm, the first shear crack appeared earlier, with noticeable increases of 19% and 31%, respectively. Beams with a 37.5 mm aggregate size showed a smaller increase of about 12%.

Regarding shear strength, the maximum values were obtained when the aggregate sizes were 20 mm and 25 mm. These values were higher than those of the reference sample (AG-CG-a/d-8) by 12% and 24%, respectively. In contrast, deep beams with aggregate sizes of 14 mm and 37.5 mm showed decreases in shear strength of approximately 5% and 3%, respectively. The results are presented in Table 12 and Figure 6.

Table 12. Effect size of coarse aggregate on the first shear cracking and shear strength when a/d = 0.8

Group	Beam Name	V <sub>cr</sub> (kN)	V <sub>n</sub> (kN)	$\Delta_f$ (mm)	%Changing of Shear Cracking Load According to (AG-CG-a/d-6)	%Changing of Shear Strength According to (AG-CG-a/d-6)
	AG-CG-a/d-8	80	282.5	2.2	---	---
	AG-14-a/d-8	70	267.5	2.8	-13%	-5%
B	AG-20-a/d-8	95	315	2.5	19%	12%
	AG-25-a/d-8	105	350	2.68	31%	24%
	AG-37.5-a/d-8	80	275	2.77	3%	-3%

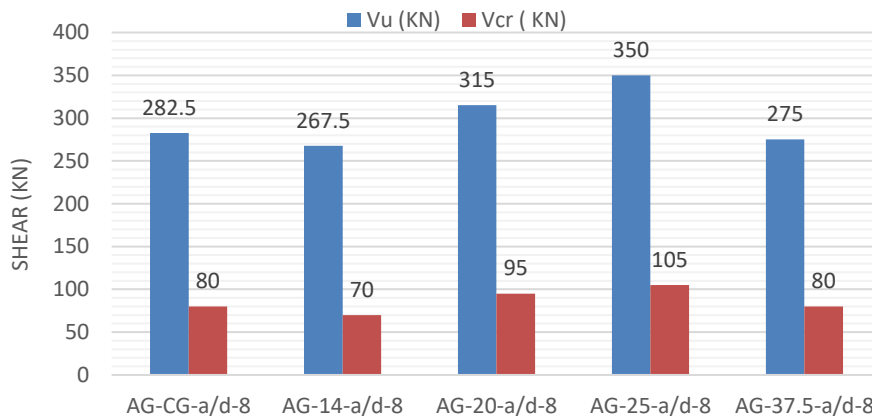


Figure 10. Effects of coarse aggregate on the first shear cracking and shear strength when a/d = 0.8

As in group (A), all deep beams tested in this group had a diagonal splitting failure mode, but the number of cracks in this group was less than group (A), and its distribution is clearer. About AG-20-a/d-8, it was noticed that concrete close to load positions was destroyed.

From Tables 4–10, it was observed that the maximum deflections occurred in the concrete deep beams with coarse aggregate sizes of 14 mm and 37.5 mm, measuring 3.35 mm and 3.3 mm, respectively. In comparison, the deflections for beams with 20 mm and 25 mm aggregate sizes were lower, at 2.35 mm and 2.81 mm, respectively. These values should be considered alongside the clear differences in the maximum load carried by each sample. The curves shown in Figures 11–12 illustrate how the size of coarse aggregate affects the load mid-span deflection of deep beams containing a single aggregate size.

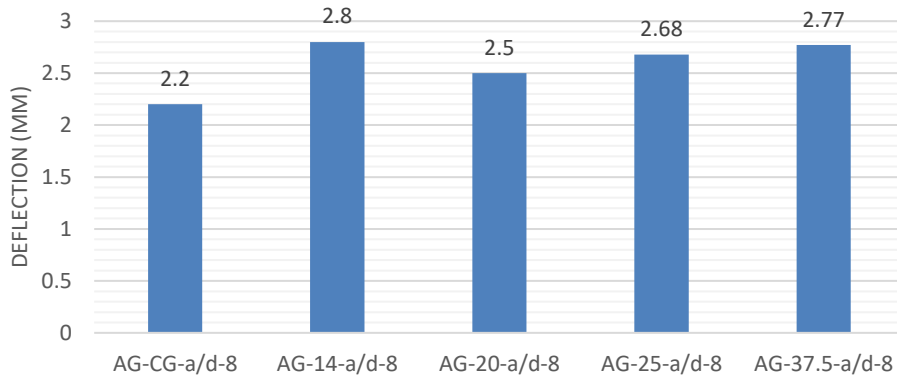


Figure 11. Effect size of coarse aggregate on load mid-span deflection when a/d = 0.8

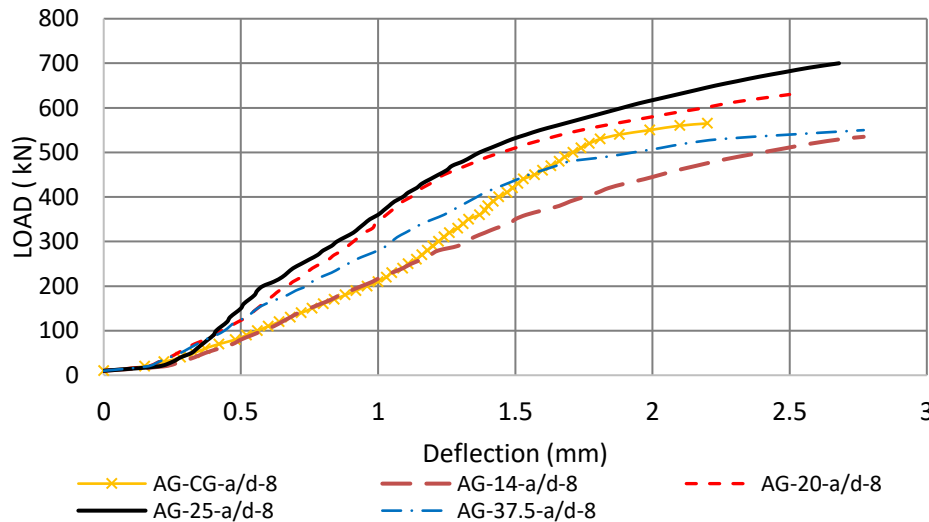


Figure 12. Effect size of coarse aggregate on load mid-span deflection when a/d = 0.8

**3.1.3. Group (C); a/d=1**

It was found that there was a noticeable decrease in the first shear crack by 12% for the beam with a coarse aggregate size of 14 mm relative to the reference sample with continuous gradation of coarse aggregate (AG-CG-a/d-1). As for the remaining three beams with coarse aggregate sizes 20, 25, and 37.5, it was found that the increase was by 8%, 12%, and 4% respectively.

Regarding the shear strength, the percentage of changes in this group was not the same as the previous groups because changing the a/d ratio, a decrease in the shear strength values was also observed for the two samples of size 14 mm and 37.5 mm by 7% and 1% compared to the reference sample AG-CG-a/d-1. The other samples showed an increase in the shear strength values; the increment in the concrete deep beam with coarse aggregate size 20 was 1% and with size 25 it was 13%. All details mentioned are illustrated in Table 13 and Figure 13.

Table 13. Effect size of coarse aggregate on the first shear cracking and shear strength when a/d = 1

Group	Beam Name	V <sub>cr</sub> (kN)	V <sub>n</sub> (kN)	Δ <sub>f</sub> (mm)	% Changing of Shear Cracking Load According to (AG-CG-a/d-6)	% Changing of Shear Strength According to (AG-CG-a/d-6)
C	AG-CG-a/d-1	62.5	247.5	2.32	---	---
	AG-14-a/d-1	55	230	3.18	-12%	-7%
	AG-20-a/d-1	67.5	250	2.71	8%	1%
	AG-25-a/d-1	70	280	2.9	12%	13%
	AG-37.5-a/d-1	65	245	3.01	4%	-1%

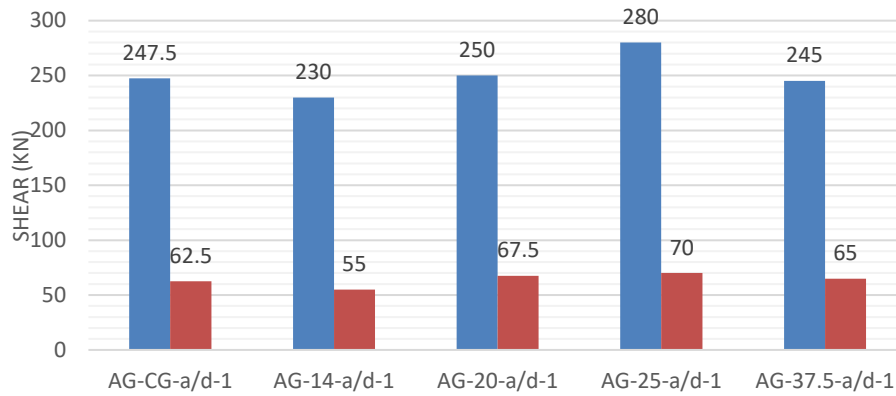


Figure 13. Effect size of coarse aggregate on the first shear cracking and shear strength when  $a/d = 1$

The deep beams tested in this group exhibited a diagonal splitting failure mode, as shown in Figure 14. Many cracks were distributed above the inclined strut zone (line of failure) in sample AG-25-a/d-1. Similarly, in sample AG-37.5-a/d-1, some cracks were observed above the inclined strut zone, on the gross section side, and on the upper face of the deep beam, as illustrated in Figure 14.



Figure 14. Crack pattern after testing for beam (AG-37.5-a/d-1)

It is worth noting that this group has a  $a/d$  ratio equal to 1. Therefore, the reference deep beam sample (AG-CG-a/d-1) tends to bend more than the reference samples from the other groups, as shown by the values in Figures 15 and 16 and Tables 4–11. Considering the ultimate load, the sample with a coarse aggregate size of 25 mm exhibited the least deflection and the highest load-bearing capacity, with a deflection of 2.01 mm. The reference sample with a continuous gradient showed a deflection of 2.28 mm. However, when the coarse aggregate size was 14 mm and 20 mm, the deflections increased to 2.3 mm and 2.71 mm, respectively. The greatest deflection, 3.2 mm, was recorded in the concrete deep beam with a coarse aggregate size of 37.5 mm.

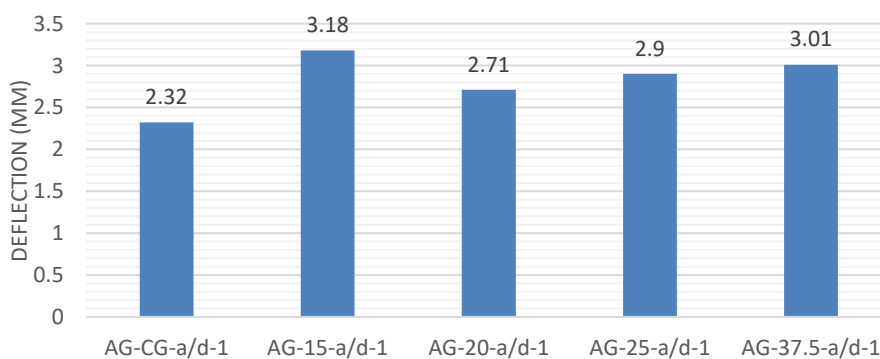


Figure 15. Effect size of coarse aggregate on load mid-span deflection when  $a/d = 1$

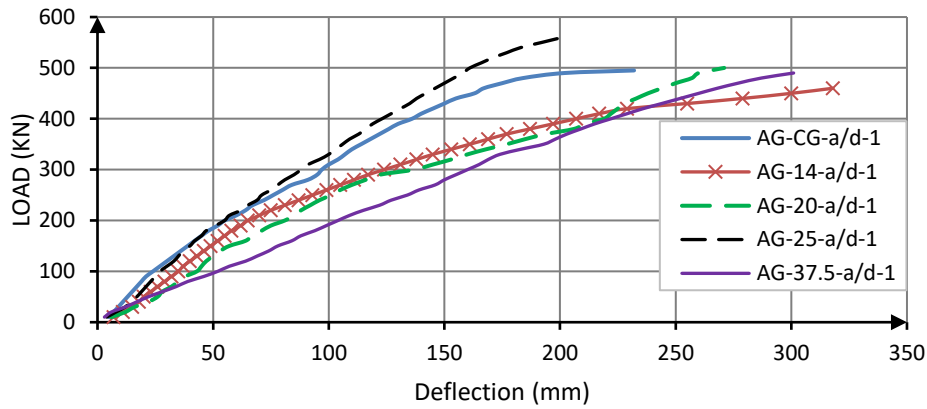


Figure 16. Effect size of coarse aggregate on load mid-span deflection when  $a/d = 1$

**3.2. Effect of shear span to effective depth ratio (a/d)**

In this section, the influences of the considered parameter shear span to effective depth ratio ( $a/d$ ), on the first shear crack and shear strength capacity, and load-deflection response are elaborately highlighted.

**3.2.1. First shear crack and shear strength**

The effect of the parameter ( $a/d$ ) on the first shear crack and shear strength, and the ratio between them for all concrete deep beams containing a single size of coarse aggregate tested in this study, is detailed and presented in Table 14 and Figures 17 and 18. This effect is studied for cases of variation in coarse aggregate size. The detailed data show that for all cases, increasing the  $a/d$  ratio from 0.6 to 1 resulted in a decrease in the first shear fracture and ultimate load. The controlling tension stresses at failure are increased by raising the  $a/d$  ratio either by increasing the bending moment at the center of the shear span or by increasing the load component perpendicular to the line connecting the load with the support points.

Between 29% and 42% fewer initial shear fractures occur as a result of increasing  $a/d$  ratio, with an average decrease of 35% across all samples. Concrete deep beams with continuous grading saw a decrease of roughly 29%, while those with only 25mm aggregate had a bigger reduction of 42%.

Increases in the  $a/d$  ratio lead to reductions in shear strength ranging from 15% to 28% (23% as the median average reduction in all situations). The decrease was greater and equivalent to 28% for both concrete deep beams with aggregate sizes of 20mm and 25mm. From these findings, it can be inferred that the reduction in first shear fracture is more dramatic than that in shear strength, where the average for first shear crack is 35% and the average for shear strength is 23%.

For  $a/d = 0.6$ , the ratio between cracking and shear strength varies from 28% to 32% (30% like a typical mean value), from 26% to 32% (29% like a typical mean value), and from 24% to 27% (26% like a typical mean value) for  $a/d = 1$ . In general, this ratio declines as the  $a/d$  ratio rises.

Table 14.  $a/d$  ratios' effects on ultimate loads and cracking

Aggregate Size (mm)	a/d=0.6			a/d=0.8			a/d=1			%Variation due to increasing (a/d)	
	V <sub>cr</sub> (kN)	V <sub>n</sub> (kN)	V <sub>cr</sub> /V <sub>n</sub>	V <sub>cr</sub> (kN)	V <sub>n</sub> (kN)	V <sub>cr</sub> /V <sub>n</sub>	V <sub>cr</sub> (kN)	V <sub>n</sub> (kN)	V <sub>cr</sub> /V <sub>n</sub>	ΔV <sub>cr</sub>	ΔV <sub>n</sub>
CG	87.5	292.5	30%	80	282.5	28%	62.5	247.5	25%	-29%	-15%
14	82.5	282.5	29%	70	267.5	26%	55	230	24%	-33%	-19%
20	112.5	347.5	32%	95	315	30%	67.5	250	27%	-40%	-28%
25	120	390	31%	105	350	30%	70	280	25%	-42%	-28%
37.5	100	335	30%	80	275	29%	65	245	27%	-35%	-27%
Average Value			30%			29%			26%	-36%	-23%

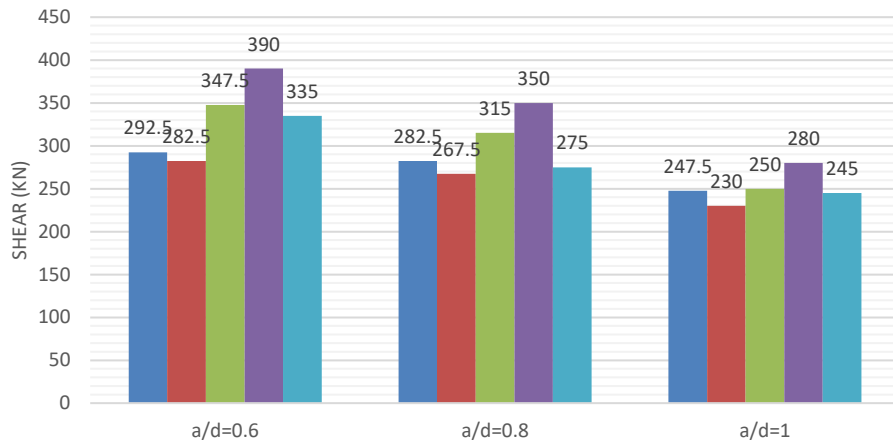


Figure 17. Effect of the a/d ratio on shear strength

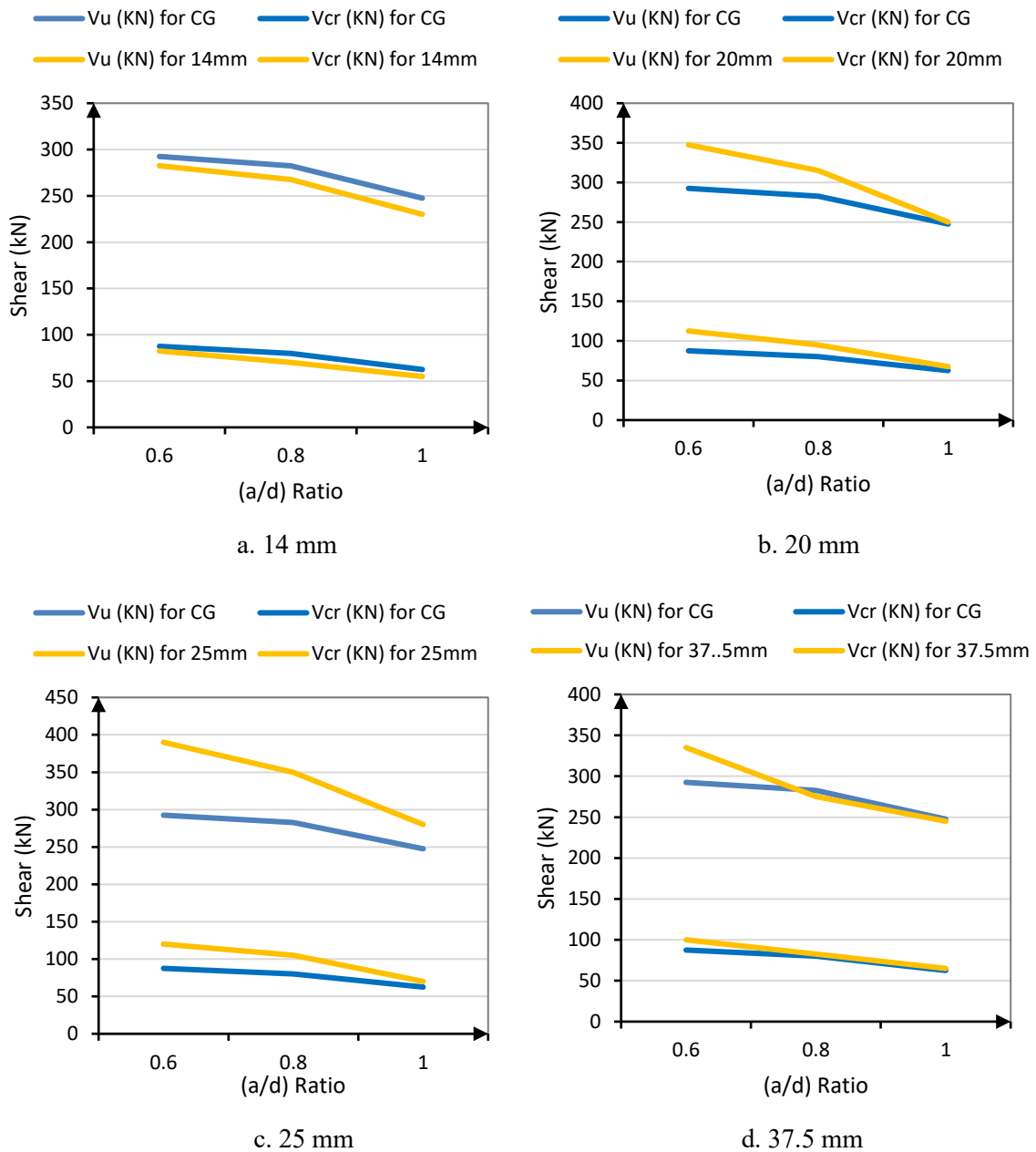


Figure 18. First shear crack and shear strength related to a/d ratio

**3.2.2. Load-deflection response**

The load-deflection response of concrete deep beams with a single size of coarse aggregate is explored in relation to the  $a/d$  ratio.

The concrete deep beams with continuous gradation were collected in a group to display the effect of changing shear span to effective depth ratio  $a/d$  on the load-deflection response, as well as for the samples with sizes 14, 20, 25, 37.5 mm, and they were collected in Figures 19–23 to illustrate the effect clearly.

The deflection value for all load stages is greatly increased by an increase in the  $a/d$  ratio. As the applied load rises, this increase grows.

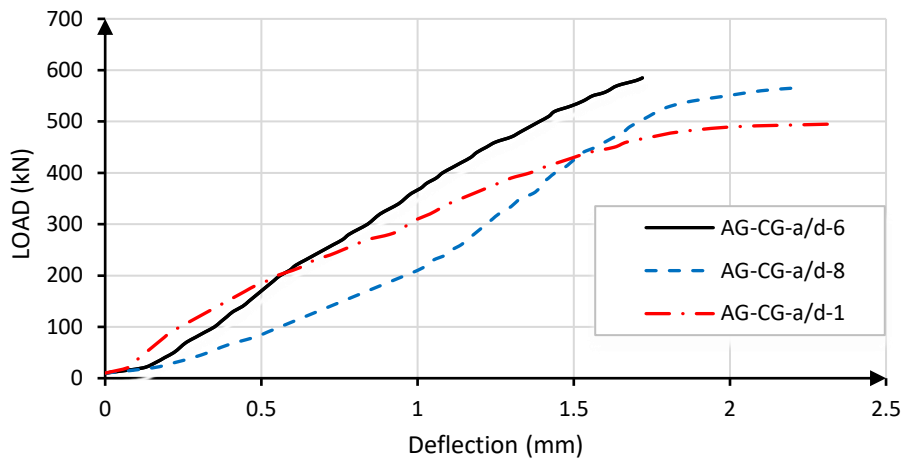


Figure 19.  $a/d$  ratio effect on deep beam load-deflection response with continuous grading of coarse aggregate

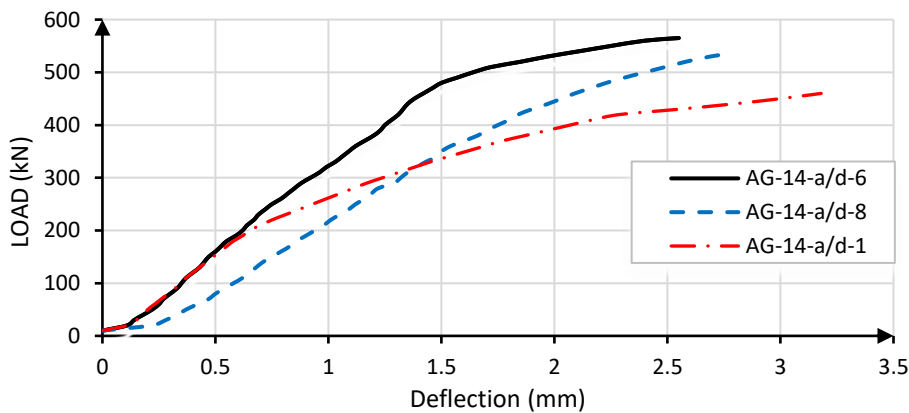


Figure 20.  $a/d$  ratio effect on deep beam load-deflection response with 14 mm coarse aggregate size

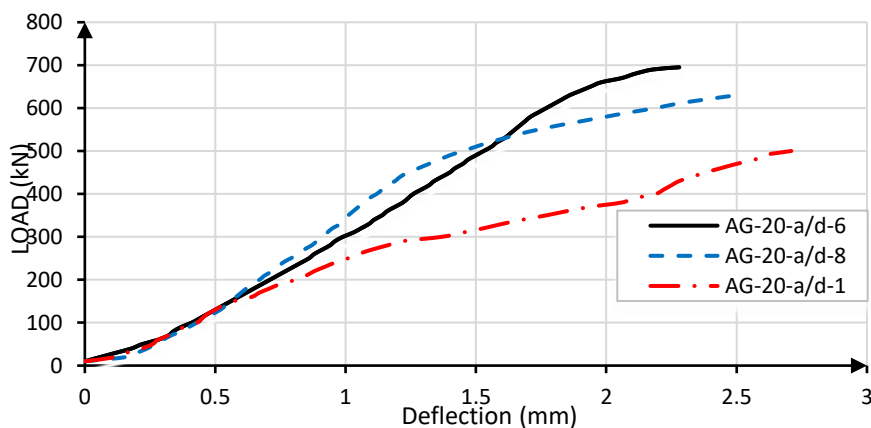


Figure 21.  $a/d$  ratio effect on deep beam load-deflection response with 20 mm coarse aggregate size

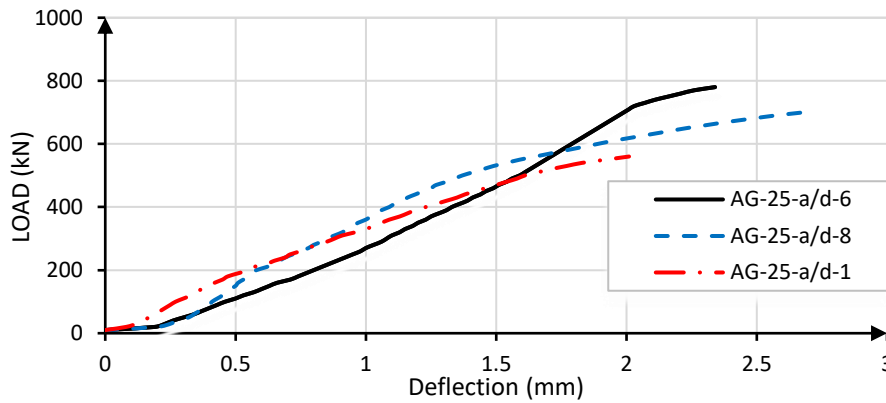


Figure 22.  $a/d$  ratio effect on deep beam load-deflection response with 25 mm coarse aggregate size

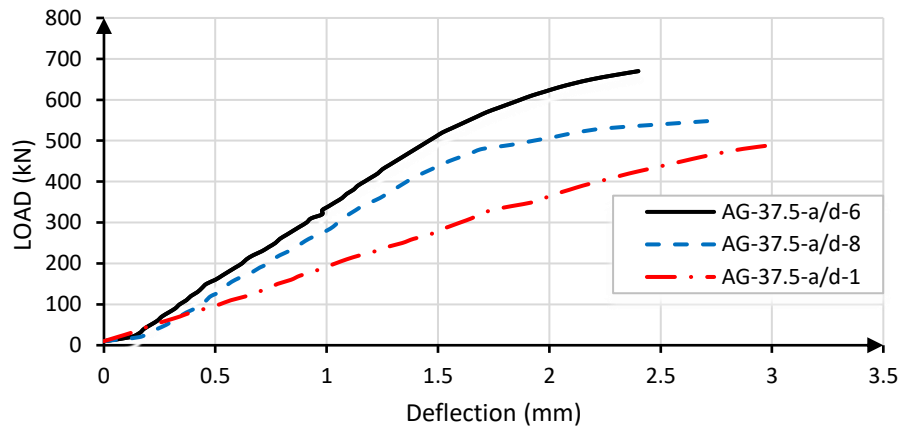


Figure 23.  $a/d$  ratio effect on deep beam load-deflection response with 37.5 mm coarse aggregate size

#### 4. Discussion

Based on all the experimental tests presented in this paper, the results are analyzed and discussed as follows. The behavior of deep beams with a single size of coarse aggregate showed variations in shear strength depending on the aggregate size and the shear span-to-depth ratio ( $a/d$ ). In general, the observed reduction in strength for specimens with aggregate sizes of 14 mm and 37.5 mm can be attributed to the same reasons discussed previously. Additionally, the strut region, which is subjected to compression, primarily depends on the material from which the deep beam is cast and its inherent properties. Therefore, the critical failure observed in this study represents the failure mode that most clearly reflects the material characteristics of the deep beam as a structural element.

It is worth noting that laboratory tests that give the mechanical properties of the material do not fully predict the behavior of a deep beam with a single coarse aggregate size, and this is clear in this research. The reason is that the deep beams have many different determinants, as the high depth and the area of the lateral face, interspersed with cracks for this structural element, make its behavior different according to the research parameters.

#### 5. Conclusion

1. A deep beam with a coarse aggregate size of 14 mm exhibited decreases in the first shear crack load and shear strength by 6% and 3%, respectively, for an  $a/d$  ratio of 0.6; by 13% and 5% for  $a/d=0.8$ ; and by 12% and 7% for  $a/d=1.0$ , compared with the concrete deep beam with continuous grading.
2. A deep beam with a coarse aggregate size of 20 mm showed increases in the first shear crack load and shear strength by 29% and 19%, respectively, for  $a/d=0.6$ ; by 19% and 12% for  $a/d=0.8$ ; and by 8% and 1% for  $a/d=1.0$ , compared with the beam with continuous grading.

3. A deep beam with a coarse aggregate size of 25 mm demonstrated increases in the first shear crack load and shear strength by 37% and 33%, respectively, for  $a/d=0.66$ ; by 31% and 24% for  $a/d=0.8$ ; and by 12% and 13% for  $a/d=1.0$ , relative to the beam with continuous grading.
4. A deep beam with a coarse aggregate size of 37.5 mm showed an increase in the first shear crack load by 14% and shear strength by 15% for  $a/d=0.6$ . For  $a/d=0.8$ , the first shear crack load increased by 3% while the shear strength decreased by 3%. For  $a/d=1.0$ , the first shear crack load increased by 4% and the shear strength decreased by 1%, compared with the beam with continuous grading.
5. It was observed that, for all cases, increasing the  $a/d$  ratio from 0.6 to 1.0 resulted in a reduction in both the cracking load and the shear strength.
6. The reduction in cracking load due to the increase in the  $a/d$  ratio ranged between 29% and 42%, with an average decrease of approximately 35% across all specimens. Deep beams with continuous grading showed a reduction of about 29%, while those with 25 mm aggregate exhibited the highest reduction of 42%.
7. Increasing the  $a/d$  ratio produced a reduction in shear strength ranging from 15% to 28%, with an average decrease of about 23% across all specimens. The reduction was nearly identical (around 28%) for beams with aggregate sizes of 20 mm and 25 mm.
8. Regarding load–deflection behavior, an increase in the  $a/d$  ratio significantly increased the deflection values at all load stages, with the magnitude of deflection growth becoming more pronounced as the applied load increased.

#### **Declaration of competing interest**

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

#### **Authors' contributions**

Mosa Jumaa Mosa: Conceptualization, methodology, data analysis, and writing the original draft. Husain Khalaf Jarallah: Literature review, data collection, and contributing to the writing and editing of the manuscript. Mohammed Mosleh Salman: Supervision, project administration, and contributing to the overall research design and methodology. All authors have read and approved the final manuscript and agree to be accountable for the accuracy and integrity of the work.

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