




Challenge Journal of CONCRETE RESEARCH LETTERS

Research Article

Effects of maximum aggregate grain size and gradation on roller compacted concrete pavements

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ABSTRACT

Roller compacted concrete (RCC) pavements, which stand out as an alternative to conventional concrete and asphalt pavements, are increasingly preferred because of their high strength, fast construction, and low cost advantages. The properties of aggregates directly affect the performance in roller compacted concrete mixtures. In particular, the maximum aggregate particle size (D_{max}) and gradation play a determining influence on the mixture's density, compressibility, and mechanical strength. This study aimed to investigate the effects of maximum aggregate particle size and gradation on the mechanical performance of roller compacted concrete pavement mixtures. Within this scope, roller compacted concrete pavement mixtures were produced using three D_{max} (12.5, 19, and 25 mm) and three different cement dosages (300, 350, and 400 kg). Tests for physical properties on mixtures were conducted using unit weight and ultrasonic pulse velocity (UPV) tests, while tests for mechanical properties were conducted using compressive strength, flexural strength, and splitting tensile strength tests. Increasing the D_{max} to 25 mm significantly improved the compressive and flexural strength of the mixtures. However, the splitting tensile strength increased up to 19 mm and showed a slight decrease when reaching 25 mm. The increase in cement content consistently improved all mechanical properties. Overall, the use of well-graded coarse aggregates with D_{max} in the range of 19–25 mm was found to improve the mechanical properties and compressibility of roller compacted concrete mixtures.

ARTICLE INFO

Article history:

Received – October 17, 2025

Revision requested – January 5, 2026

Revision received – January 22, 2026

Accepted – February 1, 2026

Keywords:

Roller compacted concrete pavement

Aggregate grain size

Mechanical properties

Ultrasonic pulse velocity



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Citation: Keleş ÖF (2026). Effects of maximum aggregate grain size and gradation on roller compacted concrete pavements. *Challenge Journal of Concrete Research Letters*, 17(1), 57–70.

1. Introduction

In recent years, while concrete and asphalt pavement construction has shown significant development, producing durable and longer-lasting pavements has become an important aim (Maafi et al. 2025). Concrete pavements have a higher modulus of elasticity and stiffness than flexible pavements and are more economical in the long term, making them the preferred choice (Baş 2024). With the emergence of new materials and advances in construction technology, various types of pavements have emerged. The most notable of these are RCC pavements and have become a type of pavement

which has been increasingly used in most countries in recent times (Ghahari et al. 2017; Tavakoli et al. 2021). RCC pavement is a rigid, zero-slump concrete that is often used in road pavements due to its rapid construction and lower cost effectiveness (ACI 325 2001, Rao et al. 2016a). The materials used in RCC pavement mixtures are similar to those in conventional concrete and contain the same components as traditional concrete (Keleş and Akpınar 2022; Çalış and Yıldız 2019). RCC pavement construction has become an important alternative to traditional concrete and asphalt pavements due to its advantages of low cement content, rapid constructability, and low maintenance costs (Aghaeipour and

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Madhkhan 2020). The recent preference for RCC pavements over other pavement types has attracted more interest and research from researchers. This situation has caused an increase in studies related to RCC pavements in recent times (Şermet et al. 2024; Armağan; et al. 2019; Sarı et al. 2025; Şengün 2024; Kılıç and Gök 2021).

The physical, mechanical, and durability characteristics of concrete are directly dependent on the design of the mixture and the specifications of the conventional or alternative aggregates used in this design. (Şengül et al. 2013). In this respect, many factors including the ingredients and aggregate characteristics govern concrete performance, and practical constraints such as the availability of local materials can limit the aggregate sources and gradations that can be used (Yıldız 2023). Aggregates, which have many properties such as shape, roughness, specific gravity, chemical composition, and stability that are related to the characteristics of the parent soil, constitute approximately 75% of concrete and play an important role in its performance (Bulut 2024a). RCC pavements differ from traditional concrete in that they contain more aggregate and less cement (Keleş et al. 2024). This makes aggregate selection even more important for RCC pavements. The particle shape, surface structure, particle size distribution, and especially the D_{max} of aggregates have a direct effect on the performance of concrete (Islam et al. 2018; Sağlam and Kılıç 2021). D_{max} has a considerable impact on many important properties of both fresh and hardened concrete (Rao et al. 2016b; Meddah et al. 2011).

Studies using recycled, artificial, industrial by-product, and waste-based aggregates of different types and sizes instead of natural traditional aggregates in concrete or asphalt production are available in the literature (Bulut 2024b; Buritatum et al. 2022; Çolak et al. 2025; Bulut and Kandil 2025; Oreto et al. 2024). In many studies in recent years, the effects of maximum aggregate particle size on concrete have been investigated. Gora and Szafraniec (2020) examined the effects of maximum aggregate particle size on the strength properties and elastic modulus of concrete in their study. In this context, concrete specimens with D_{max} values of 8, 16, and 31.5 mm were produced, and as D_{max} increment, a significant decrease in splitting tensile strength and a slight increase in compressive strength were observed. Śliwiński and Duży (2020) investigated the effect of the ratio of the minimum size of cubic concrete specimens to the D_{max} . It was found that the relationship between specimen size and D_{max} had a noticeable effect on the representativeness of concrete specimens. Mahmoud et al. (2020) found that increasing the D_{max} used in concrete reduces the mass attenuation coefficient. Siregar et al. (2017) investigated the effect of aggregate size distribution on the fracture behavior of concrete with high strength. It was determined that size distribution affects the level of ductility exhibited by concrete with high strength. Çelikten and Canbaz (2020) investigated the effect of aggregate particle size on the permeability properties of concrete. It has been determined that an increment in the aggregate particle size within mixtures causes a decrease in strength. Faramarzi and Rezaee (2018) examined the strength prop-

erties of concrete specimens according to changes in particle size. For this objective, concrete blocks with particle sizes of 12, 20, and 25 mm were produced. It was determined that an increase in aggregate size increases compressive strength. Furthermore, the results of the flexural tests showed that fracture toughness increased as the particle size changed from 12 mm to 20 mm, and decreased slightly when the particle size changed from 20 mm to 25 mm. Türkmenoğlu and Atahan (2020) focused on the impact of aggregate grain size distribution and PP fiber usage on plastic shrinkage cracking in concrete. It was determined that coarse aggregate grain size distribution is more effective in preventing cracking. Although many studies have been investigated regarding the impact of maximum aggregate grain size on conventional concrete, its effects on RCC have been studied very limitedly. Furthermore, the effect of D_{max} on RCC pavements has almost not been investigated. Sağlam and Kılıç (2021) produced RCC mixtures with dosages of 300 kg and 350 kg, with D_{max} of 12.5, 16, and 22.4 mm. In low cement dosage mixtures, the maximum compressive strength is observed using the largest aggregate size, while in high-cement mixtures, it is obtained with the smallest aggregate size. Rao et al. (2016b) investigated the effect of maximum aggregate sizes on RCC performance. It was reported that as aggregate size increased, strength increased but permeability properties deteriorated.

In this study, the effects of different D_{max} on the physical and mechanical properties of RCC pavements were experimentally investigated. Unlike previous studies, RCC pavement mixtures with three different D_{max} 12.5, 19, and 25 mm were produced according to the mixture design specified in ACPA (2014a). In addition to different aggregate particle sizes, the mixtures had three different cement contents: 300, 350, and 400 kg. Optimum water contents for maximum compactibility were determined for each mixture. The mechanical properties of RCC pavement mixtures with different particle sizes and cement dosages, including compressive, flexural, and splitting tensile strength, as well as their UPV and unit weight values, were measured and the test results have been correlated.

2. Materials and Experimental Program

2.1. Materials

In this study, crushed limestone aggregate has been used in according with ASTM C33 (2016) standard. To produce the mixtures, the maximum aggregate particle sizes specified by the American Concrete Pavement Association (ACPA 2014b) were considered and selected as 12.5 mm, 19 mm, and 25 mm. The aggregate particle size ranges were 0-5 mm, 5-12.5 mm, 12.5-19 mm, and 19-25 mm (Fig. 1). The properties of coarse and fine aggregates used in the study obtained in according with ASTM C127 (2016) and ASTM C128 (2016) standards are given in Table 1.

The sieve size ranges according to D_{max} (12.5, 19, and 25 mm) are given in Table 2. The gradation curves of the mixture aggregates created within the sieve size ranges

specified by the ACPA (2014b) are given in Fig. 2 according to the maximum aggregate particle sizes. Three different aggregate mixtures were prepared to produce RCC pavement mixtures. Mixture 1 had a maximum aggregate particle size of 12.5 mm, with aggregate particle size ranges of 0-5 mm and 5-12.5 mm. Mixture 2 had a maximum aggregate particle size of 19 mm, with aggregate particle size ranges of 0-5 mm, 5-12.5 mm, and 12.5-19 mm. Mixture 3 had a maximum aggregate particle size

of 25 mm, with aggregate particle size ranges of 0-5 mm, 5-12.5 mm, 12.5-19 mm, and 19-25 mm.

In the study, CEM II 42.5 Portland cement was used according to the ASTM C150 (2011) standard. The properties of the cement used are given in Table 3. Three different cement dosages, 300 kg, 350 kg, and 400 kg, were used in the RCC mixtures. City supply water according to ASTM C1602 (2012) standard was used in the production of RCC pavement mixtures.



Fig. 1. Coarse aggregates used in RCC mixtures.

Table 1. Properties of coarse and fine aggregates used in RCC mixtures.

Physical properties	Fine aggregate (0-5 mm)	Coarse aggregate (5-12.5 mm)	Coarse aggregate (12.5-19 mm)	Coarse aggregate (19-25 mm)
Specific gravity (OD), gr/cm ³	2.48	2.68	2.67	2.67
Specific gravity (SSD), gr/cm ³	2.57	2.69	2.68	2.68
Apparent specific gravity, gr/cm ³	2.71	2.72	2.69	2.70
Absorption, %	3.51	0.55	0.27	0.38

Table 2. Combined aggregate gradation ranges for RCC (ACPA 2014b).

Sieve size	Lower & Upper specification limits 12.5 mm		Lower & Upper specification limits 19 mm		Lower & Upper specification limits 25 mm	
	Lower	Upper	Lower	Upper	Lower	Upper
37.5 mm	-	-	-	-	100	100
25 mm	-	-	100	100	82	100
19 mm	100	100	95	100	72	95
12.5 mm	81	100	70	95	61	81
9.5 mm	71	91	60	85	50	71
4.75 mm	49	70	40	60	36	55
2.36 mm	33	54	30	50	25	43
1.18 mm	24	40	20	40	15	32
600 µm	15	30	15	30	10	26
300µm	10	25	10	25	5	19
150 µm	2	16	2	16	2	16
75 µm	0	8	0	8	0	8

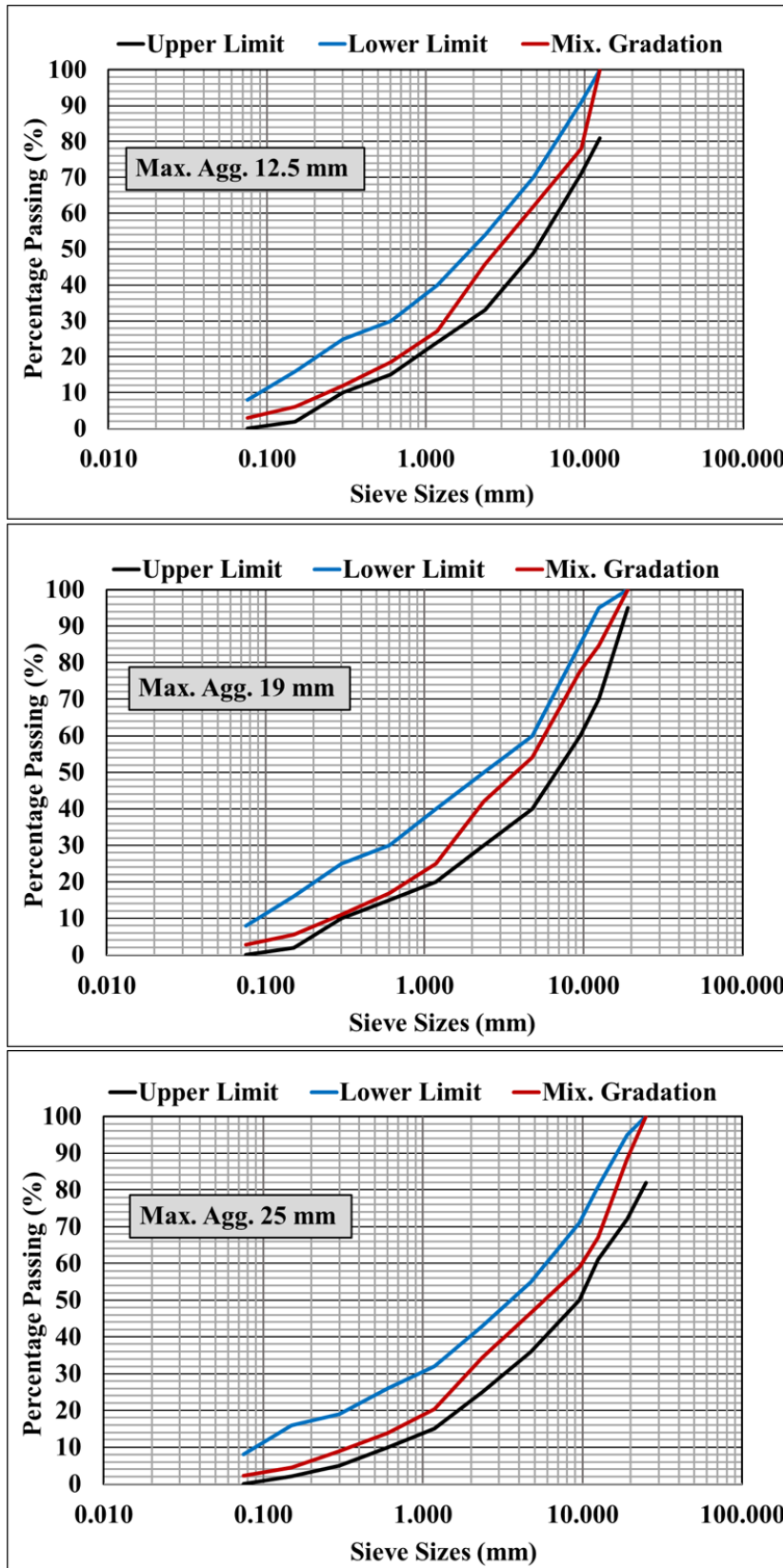


Fig. 2. Gradation curves of combined aggregate and standard limitations.

Table 3. Properties of cement used in RCC mixtures.

Component	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	Na ₂ O	K ₂ O	Cl
Amount (%)	18.5	4.5	3.6	63.3	1.2	2.9	0.3	0.7	0.014
Initial and final setting time (min)	145–215		28-day compressive strength (MPa)				45.82		

2.2. Optimum moisture content and mix proportions

The consistency of RCC pavements is more important compared to conventional concrete pavements due to the presence of the compaction operation during production. Compaction is critical in obtaining maximum density in RCC pavements (Keleş et al. 2024). The relationship between moisture content, the parameter that most affects the compactibility of mixtures, and dry unit weight has been found by the Modified Proctor Test (ASTM D1557; 2012). The relationships between optimum moisture content and dry unit weight for mixtures with three different cement dosages are given in Fig. 3.

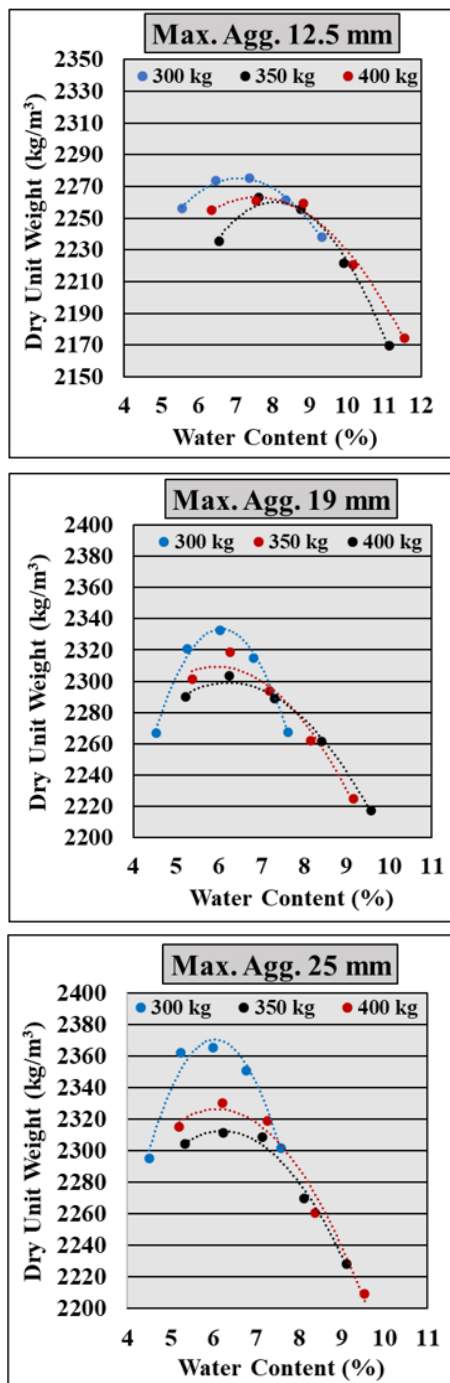


Fig. 3. The relationship between the dry unit weight and water content of RCC mixtures.

The water content and dry unit weight relationships of RCC mixtures were examined, and the water contents of the mixtures were determined by identifying the optimum moisture content corresponding to maximum density. Increasing the maximum aggregate particle size in the mixtures reduced the optimum moisture content corresponding to maximum density. As the particle size increased, the percentage of fine aggregate reduced, and the water absorption ratio of the mixes decreased. This revealed the need for less water for maximum compactibility. The material quantities required for 1 m³ of RCC mixtures were calculated according to the water contents of the mixtures, and the mixture ratios are given in Table 4. The mixture codes in the table are expressed numerically. The first part of the codes represents the D_{max} (mm), and the second part represents the cement dosage (kg).

2.3. Sample preparation

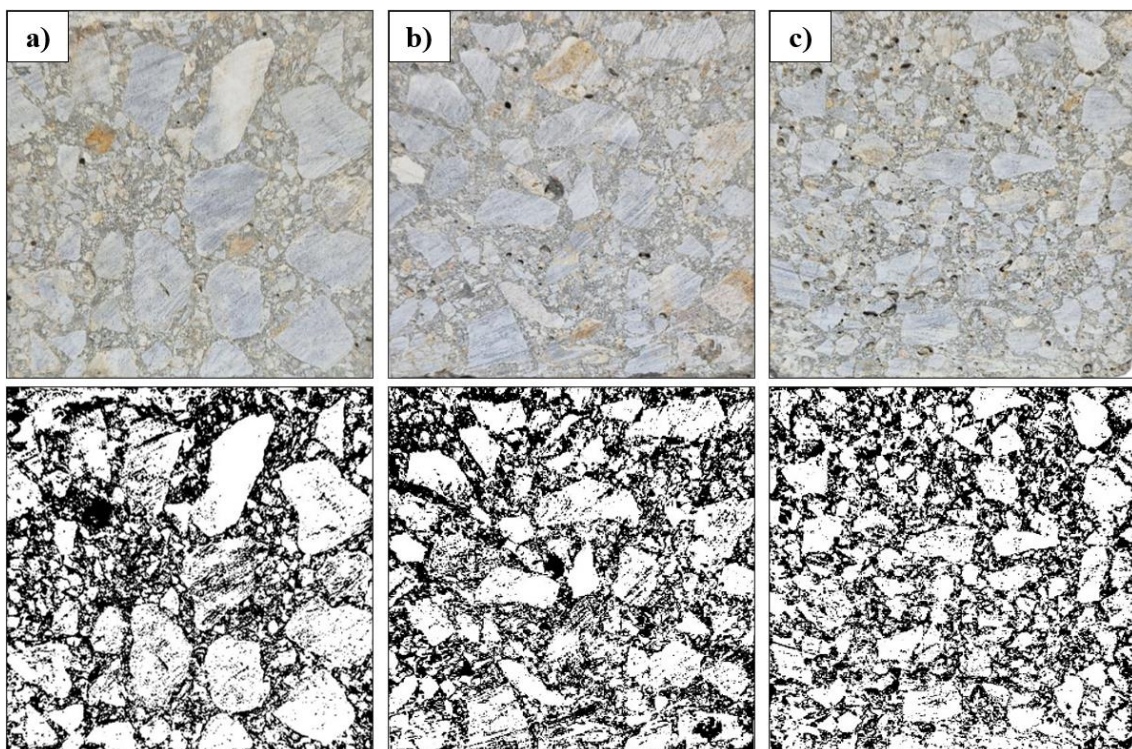
A pan-type laboratory mixer was used to produce RCC mixtures. For each mixture, the aggregates and cement were first mixed until homogeneous, then mixing water was added and mixing was continued. Unlike conventional concrete, RCC has a very dry consistency, therefore requiring additional compaction during placement. To produce RCC mixtures in a laboratory environment, the compaction procedure specified in ASTM C1435 (2017) is applied. For this purpose, vibrating hammers and compaction plates meeting the specifications outlined in the standard were used. Cylinder specimens were produced for compressive and tensile strength, beam specimens for flexural strength, and cube specimens for unit weight. Circular compaction plates were used for cylinder specimens, rectangular plates for beam specimens, and square plates for cube specimens. The RCC specimens produced using vibrating hammer, compaction plates, and molds used in specimen production are shown in Fig. 4.

According to the standard, the compaction process of the specimens was carried out in three layers, with each layer not exceeding 20 seconds. The RCC samples were demolded 24 hours following casting and kept in a curing tank in accordance with the ASTM C192 (2015) standard until the test day, which was 28 days later.

Cross-sectional images of the RCC specimens produced in accordance with the standards are presented in Fig. 5 and were obtained by cutting and photographing the beam specimens using a standard scanner. The aggregate and mortar composition in the concrete was created by drawing the edges around each particle and then filling these outlines with white. In the images arranged in this way, the white color represents the aggregate, and the black color represents the mortar surfaces. In all specimens, the aggregate particles were observed to be homogeneously distributed, and no signs of component separation were found.

Table 4. Proportions of materials used in the production of RCC specimens.

Mix. code	Cement (kg)	Aggregate (kg)				W/C
		Fine aggregate (0–5 mm)	Coarse aggregate (5–12.5 mm)	Coarse aggregate (12.5–19 mm)	Coarse aggregate (19–25 mm)	
12.5–300		1132	815	–	–	0.43
19–300	300	1030	506	404	–	0.45
25–300		843	303	303	505	0.45
12.5–350		1081	778	–	–	0.42
19–350	350	1010	496	396	–	0.38
25–350		819	295	294	490	0.40
12.5–400		1067	798	–	–	0.35
19–400	400	978	480	383	–	0.35
25–400		805	290	289	481	0.34

**Fig. 4.** Vibrating hammer, tamping plates, molds and produced RCC samples.**Fig. 5.** Cross-sectional images of RCC samples: (a) $D_{\max}=25$ mm; (b) $D_{\max}=19$ mm; (c) $D_{\max}=12.5$ mm.

2.4. Testing methods

This study evaluated the impact of maximum aggregate particle size on the certain physical and mechanical properties of RCC pavement mixtures. Within this scope, the fresh and hardened concrete unit weights, UPV values, and compressive, flexural, and splitting tensile strengths of the RCC samples were measured. The unit weights of RCC mixtures (fresh and hardened) were measured on 150x150x150 mm cube specimens according to ASTM C138 (2013) and ASTM C642 (2013) standards, respectively. The UPV test, one of the non-destructive testing methods, was applied to cylindrical, cube, and

beam specimens measuring 150x300 mm, 150x150x150 mm, and 100x100x400 mm, respectively, before the tests, in accordance with the ASTM C597 (2009) standard. Compressive strength and tensile strength in flexure tests were applied to 150x300 mm cylindrical specimens in accordance with ASTM C39 (2014) and ASTM C496 (2017) standards, respectively, while the flexural strength test was applied to 100x100x400 mm beam specimens in accordance with ASTM C78 (2018) on beam specimens measuring 100x100x400 mm. Images of the tests performed on the RCC specimens are provided in Fig. 6. Three samples were subjected to testing in order to obtain results for each experiment.

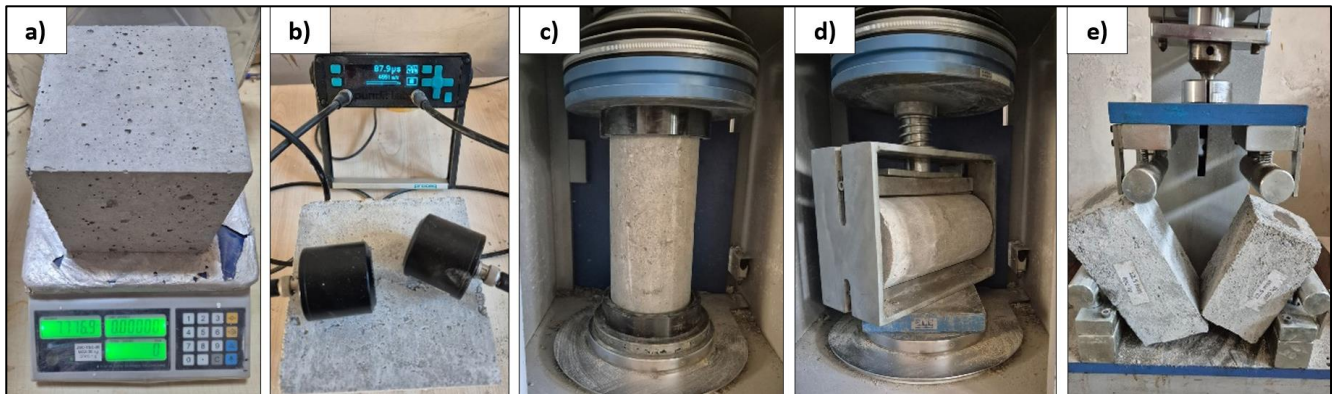


Fig. 6. RCC sample tests: (a) Unit weight; (b) UPV; (c) Compressive strength; (d) Splitting tensile strength; (e) Flexural strength.

3. Results and Discussion

3.1. Unit weight

The fresh and hardened unit weight results for RCC mixtures with different maximum aggregate sizes and

gradations are presented in Table 5 and Fig. 7. When examining the unit weight results of the RCC mixtures, it was observed that both the fresh and hardened unit weights had close values. However, with the increment in the D_{max} , slight increases were observed in both unit weights.

Table 5. Unit weights of RCC samples.

Max. aggregate grain size	Cement dosage / Unit weight (kg/m ³)					
	300 kg		350 kg		400 kg	
	Hardened	Fresh	Hardened	Fresh	Hardened	Fresh
12.5 mm	2380.19	2475.57	2344.33	2455.85	2344.30	2460.99
19 mm	2387.06	2478.65	2371.13	2479.51	2386.99	2473.24
25 mm	2397.37	2489.42	2395.55	2482.58	2392.80	2482.56

Considering the hardened unit weights, the lowest unit weight value was obtained in mixtures with a D_{max} of 12.5 mm and cement dosages of 350 kg and 400 kg, at approximately 2344 kg/m³. The highest unit weight was observed in mixtures with a maximum particle size of 12.5 mm and a dosage of 300 kg, at 2397 kg/m³. When the D_{max} changed from 12.5 mm to 25 mm at a dosage of 300 kg, the unit weight increased by approximately 1%. This increase was approximately 2% at cement dosages of 350 and 400 kg. Similarly, Çelikten and Canbaz (2020) observed an increase in unit weight with increment aggregate size in their study. Konitufe et al. (2023) used

D_{max} of 14, 20, and 25 mm in their study and found the unit weights of the mixtures to be nearly identical.

3.2. Compressive strength

The uniaxial compressive strength test results for RCC mixtures are presented in Table 6 and Fig. 8. The results show that the compressive strength of the mixtures increases steadily with increasing maximum aggregate particle size and cement dosage. Increasing the aggregate particle size from 12.5 mm to 25 mm increased the compressive strength by approximately 23% in mix-

tures with a cement dosage of 300 kg. The increase in compressive strength in RCC mixtures with cement dosages of 350 and 400 kg continued at approximately 31% and 18%, respectively. Compressive strength test results have indicated that the use of aggregates up to 25 mm in size in RCC mixtures has steadily increased the strength of the mixtures, regardless of the cement dosage. In addition, the effect of cement dosage on the compressive strength of the mixtures was similar to the maximum ag-

gregate particle size effect. Increasing the cement dosage in RCC mixtures from 300 kg to 400 kg provided strength increases of approximately 18%, 12%, and 13% for mixtures with maximum aggregate particle sizes of 12.5 mm, 19 mm, and 25 mm, respectively. The increase in cement dosage had a greater impact on the compressive strength test results of RCC mixtures with a 12.5 mm particle size compared to mixtures with 19 mm and 25 mm maximum particle sizes.

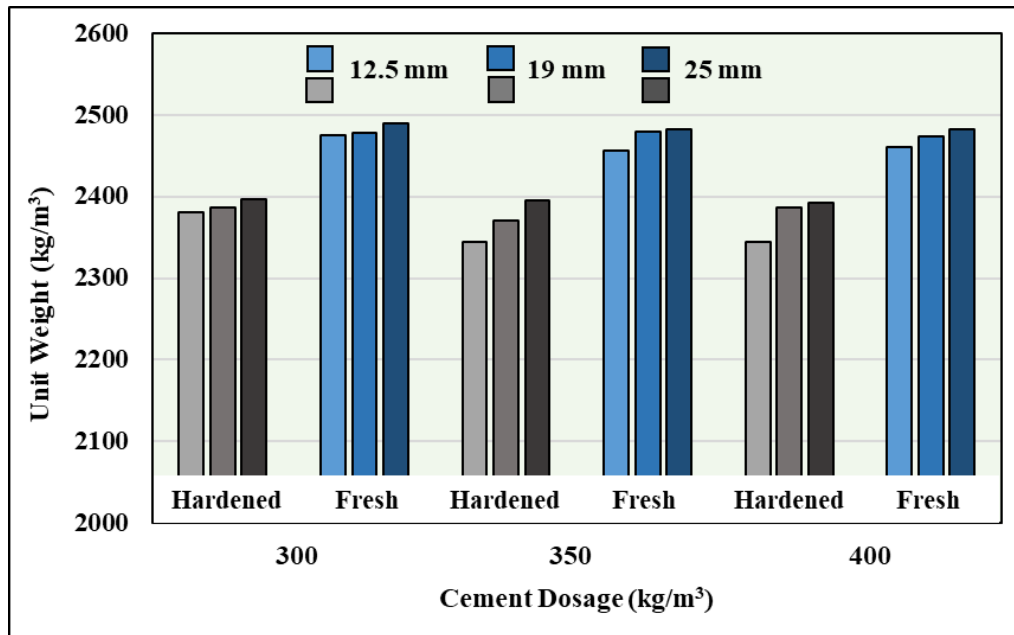


Fig. 7. Unit weights of RCC mixtures.

Table 6. Different strength test results of RCC mixture specimens.

Max. aggregate grain size	Parameter	Cement dosage (kg/m³)		
		300 kg	350 kg	400 kg
12.5 mm	Compressive strength (MPa)	41.57	41.77	48.90
19 mm		46.67	51.30	52.33
25 mm		51.07	56.13	57.65
12.5 mm	Flexural strength (MPa)	6.85	7.02	7.33
19 mm		6.87	7.07	7.62
25 mm		7.19	7.59	8.10
12.5 mm	Splitting tensile strength (MPa)	2.93	3.02	3.58
19 mm		3.43	3.47	3.75
25 mm		3.09	3.14	3.21

The results have indicated that the compressive strength test results of RCC mixtures made from aggregates of uniform size increases with increasing aggregate size. The compressive strength of RCC mixtures is largely dependent on the mechanical interlocking effect between aggregates. Increasing the D_{max} allows the aggregate skeleton to form a stronger and more rigid structure, transferring the load through aggregate-aggregate contacts. This increases the strength, particularly in RCC

mixtures with low water/cement ratios, by reducing the stress concentration on the cement paste. Additionally, increasing the maximum aggregate particle size results in a better graded aggregate distribution. This facilitates better compaction of RCC mixtures, thereby reducing the void ratio and producing denser concrete, which further enhances strength. This effect is also supported by the increase in unit weights resulting from the larger particle size.

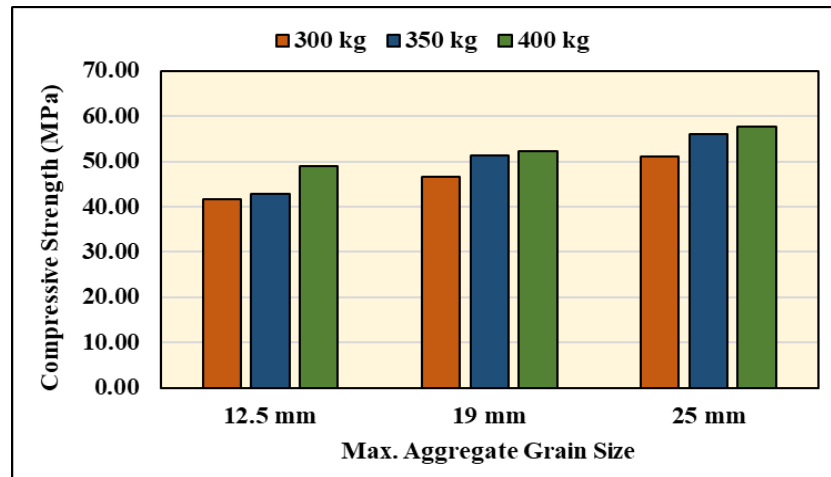


Fig. 8. Variation of compressive strength according to max. aggregate grain size.

Similar to the results of the current study, many studies have recorded increases in compressive strength with an increase in aggregate particle size. Faramarzi and Rezaee (2018), recorded increases in compressive strength with increasing aggregate particle size in their studies. A strength of 44.5 MPa was obtained in concrete mixtures with 12 mm aggregate size, while a compressive strength of 58.45 MPa was obtained in mixtures with 25 mm aggregate size. Góra and Szafraniec (2020), produced concrete mixtures with D_{max} of 8, 16, and 32 mm and obtained compressive strengths of 54.0 MPa, 54.7 MPa, and 56 MPa, respectively. Musa and Saim (2017) used two different aggregate particle sizes, 10 and 20 mm, in their studies. They determined compressive strengths of approximately 17

MPa and 39 MPa, respectively, achieving a significant strength increase of 128% with increasing particle size. In addition, Ajamu and Ige (2015) and Khan et al. (2021) were among other researchers who recorded an increase in compressive strength with an increase in D_{max} . Contrary to these studies, Konitufe et al. (2023) recorded a slight decrease in compressive strength, achieving approximately 28 MPa, 27 MPa, and 26 MPa in concrete mixtures with aggregate sizes of 14, 20, and 25 mm, respectively. Similarly, Woode et al. (2015) observed a decrease in strength with increasing maximum aggregate particle size in their studies. Together with other studies in the literature, the results showing the effect of D_{max} on compressive strength are summarized in Fig. 9.

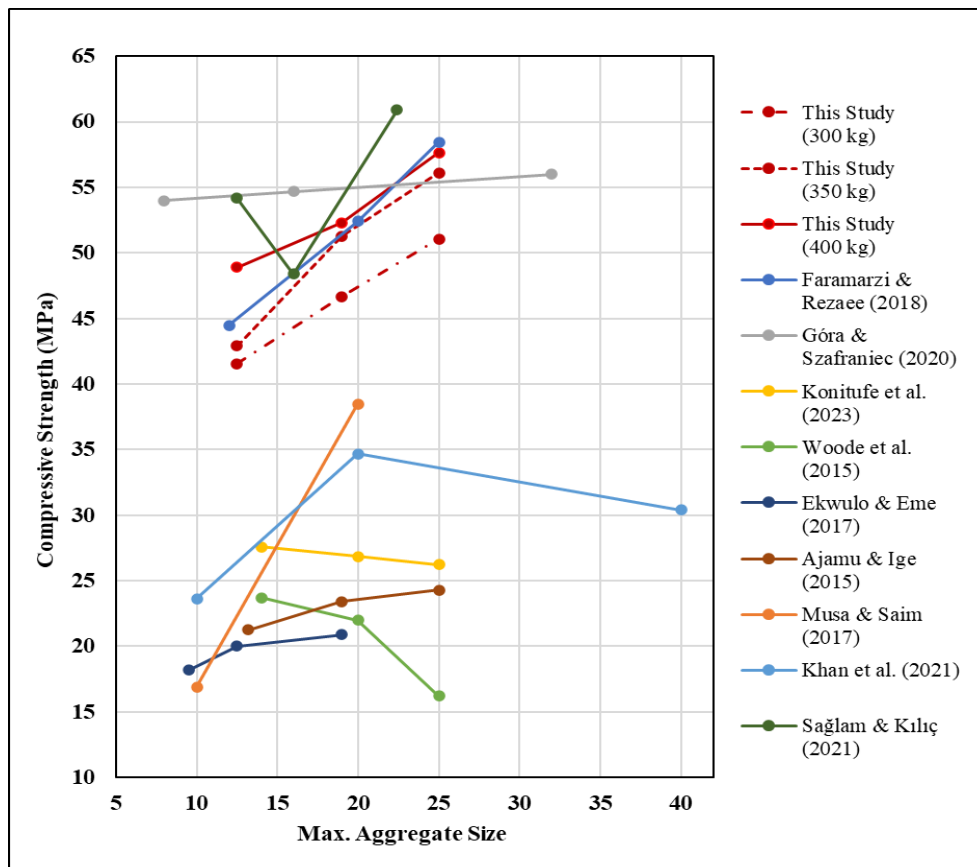


Fig. 9. The effect of D_{max} on compressive strength in different studies.

3.3. Flexural strength

The results of the four-point flexural strength test for RCC mixtures are presented in Table 4 and Fig. 10. The results have indicated that the flexural strength of the mixtures increased steadily with increasing cement dosage. The highest flexural strength was measured at 8.1 MPa in mixtures with a cement dosage of 400 kg and a maximum aggregate particle size of 25 mm. The lowest strength was measured at 6.85 MPa in specimens with a cement dosage of 300 kg and a particle size of 12.5 mm. Increment of the cement dosage in the mixtures from 300 kg to 400 kg increased the flexural strength of the samples with aggregate particle sizes of 12.5 mm, 19 mm, and 25 mm by approximately 7%, 13%, and 13%, respectively. The change in maximum aggregate particle size produced different results in flexural strength. The increase in maximum aggregate size from 12.5 mm to 19

mm produced an insignificant variation in flexural strength for the mixtures with 300 and 350 kg/m³ cement dosage. Increasing the particle size from 19 mm to 25 mm in mixtures with the same dosages resulted in approximately 6% and 7% increases in flexural strength, respectively. In mixtures with a dosage of 400 kg, changing the particle size from 12.5 mm to 19 mm and then from 19 mm to 25 mm increased the flexural strength by 4% and 6%, respectively. The American Concrete Pavement Association (ACPA 2014a) has stated that the flexural strength of RCC pavements ranges between 3.5 and 7 MPa. The Technical Specifications for Concrete Pavements published by the General Directorate of Highways of Türkiye (KGM 2016) specifies a minimum flexural strength of 4.5 MPa for concrete pavements. The flexural strength results obtained show that all mixtures meet the minimum flexural strength requirements specified in the standards.

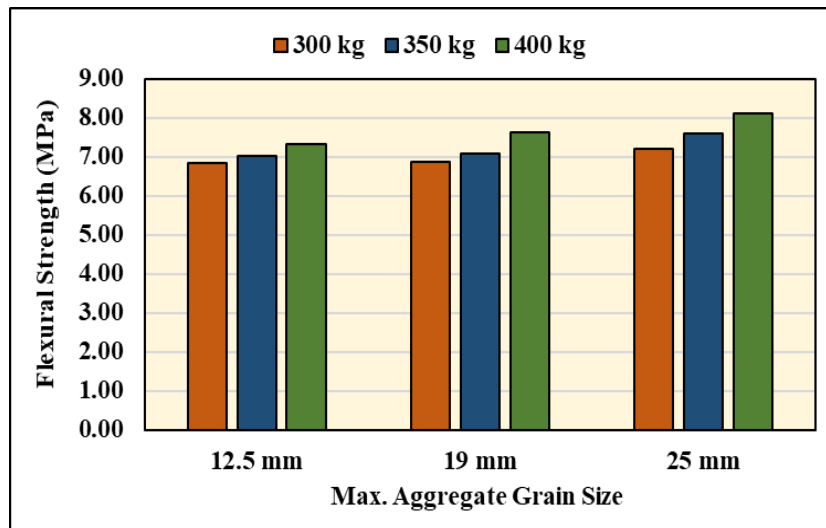


Fig. 10. Variation of flexural strength according to max. aggregate grain size.

The results showed that, similar to the compressive strength results, the flexural strength increased with the increment of the D_{max} . The increase in flexural strength can be described by the rigid structure formed by coarse aggregates limiting crack propagation and extending the crack path, thereby providing higher energy absorption under flexural loading. Furthermore, coarse aggregates reduced the mortar volume, decreasing the proportion of weak tensile zones and contributing to increased flexural strength. Furthermore, as the aggregate particle size increased, the load-bearing skeleton structure of the concrete became more rigid. Under bending, this rigid skeleton contributed to the homogeneous distribution of the load and the spreading of the bending moment over a wider area, thereby contributing to the increase in flexural strength.

Similarly, Sağlam and Kılıç (2021) reported an increase in flexural strength with an increment in maximum aggregate particle size. Flexural strength results of 7.6 MPa, 7.7 MPa, and 7.9 MPa were obtained for mixtures with maximum aggregate particle sizes of 12.5 mm, 16 mm, and 22.4 mm, respectively. The flexural strength

of the samples supported the conclusion that bigger aggregate size resulted in better performance, which in turn resulting in higher flexural strength (Wei et al. 2020). On the contrary, there are also studies showing that flexural strength decreases as aggregate particle size increases. Ajamu and Ige (2015), and Ozioko (2015) used different maximum aggregate particle diameters in their studies and observed decreases in flexural strength with increasing particle size.

3.4. Splitting tensile strength

The splitting tensile strength test results for RCC mixtures are presented in Table 4 and Fig. 11. The results showed that the splitting tensile strength of the mixtures increased steadily with higher cement dosages. The highest splitting tensile strength was measured at 3.75 MPa in mixtures with a cement dosage of 400 kg and D_{max} of 19 mm. The lowest strength was measured at 2.93 MPa in samples with a cement dosage of 300 kg and a particle size of 12.5 mm. Increment the cement dosage in the mixtures from 300 kg to 400 kg increased

the splitting tensile strength of the specimens with aggregate particle sizes of 12.5 mm, 19 mm, and 25 mm by approximately 22%, 9%, and 4%, respectively. Cement dosage had shown the minimum effect in mixtures with D_{\max} of 25 mm when compared to other aggregate sizes. Increment the D_{\max} did not cause a continuous increase in splitting tensile strength, unlike in compressive and flexural strengths. The splitting tensile strengths of the mixtures increased when the particle size reached 19

mm and began to decrease when it reached 25 mm. This was observed in all cement-dosed mixtures. The splitting tensile strengths of mixtures with cement dosages of 300 kg, 350 kg, and 400 kg increased by 17%, 15%, and 5%, respectively, as the particle size changed from 12.5 mm to 19 mm. Conversely, as the particle size increased from 19 mm to 25 mm, the splitting tensile strength in the split test decreased by 10%, 9%, and 14%, respectively.

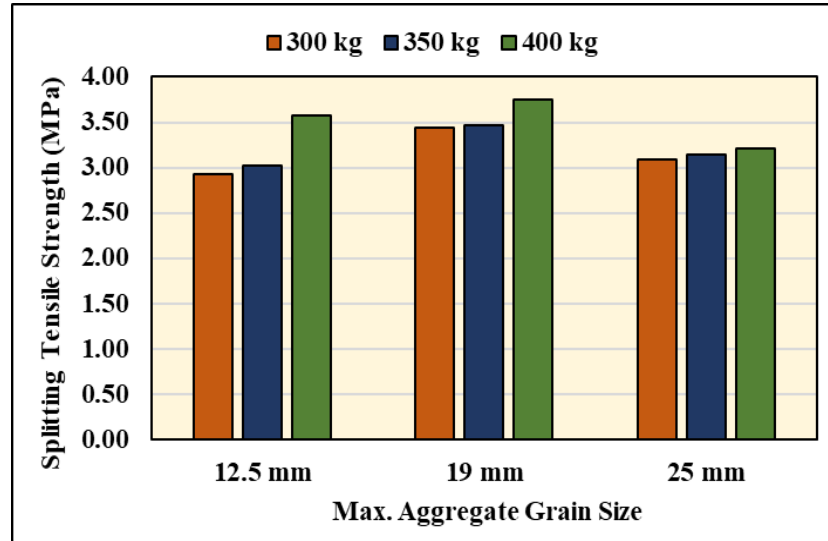


Fig. 11. Variation of splitting tensile strength according to max. aggregate grain size.

Similar to the results of this study, Wei et al. (2020) used aggregate particle sizes of 9.5 mm and 16 mm in concrete mixtures and obtained splitting tensile strengths of 2.18 MPa and 2.97 MPa, respectively. They determined that increasing the particle size resulted in an approximate 36% increase in strength. Góra and Szafrańiec (2020), on the other hand, recorded a decrease in splitting tensile strength in the split test with an increase in D_{\max} . They produced concrete mixtures with D_{\max} of 8, 16, and 32 mm and obtained splitting tensile strengths in the split test of 5.0 MPa, 3.7 MPa, and 3.3 MPa, respectively.

3.5. Ultrasonic pulse velocity (UPV)

The UPV values of each mixture measured prior to strength tests on cylinder, cube, and beam specimens. The UPV test results for RCC specimens produced in different sizes and shapes are given in Fig. 12. UPV values increased as the D_{\max} of the mixtures became larger, while these values decreased as the cement dosage amount also became higher. The best UPV values were measured at 4971 m/s, which were obtained from beam specimens with D_{\max} of 25 mm and a cement dosage of 300 kg. The lowest UPV values were measured at 4451 m/s, obtained from cylinder specimens with D_{\max} of 12.5 mm and a cement dosage of 400 kg. Considering cube specimens, the UPV values in RCC mixtures with cement dosages of 300 kg, 350 kg, and 400 kg increased by 4%, 3%, and 7%, respectively, as D_{\max} increased from 12.5 mm to 25 mm. Considering all sample results, increasing

the dosage from 300 kg to 350 kg and 400 kg caused a decrease in UPV values of approximately 1% and 2%, respectively. When evaluated in terms of sample sizes, differences in UPV values were observed despite having the same mixture. When cube, beam, and cylinder samples were compared, UPV values showed an average difference of 4%, with the highest UPV values obtained from beam samples. The UPV values of the beam specimens are followed by the cube and cylinder specimens, respectively. The UPV variability in samples of different sizes with the same mixture may be due to differences in the compaction method (Keleş and Akpınar 2022). Samples with smaller cross-sections were subjected to greater compression energy, resulting in a more void-free and dense mixture, leading to higher UPV values.

The results revealed that 85% of the RCC mixtures had UPV values exceeding 4500 m/s. The UPV values of the remaining 15% also stayed above 4000 m/s. Whitehurst (1951) evaluated the results as excellent, good, questionable, poor, and very poor in his UPV-based quality assessment method. In this method, UPV values indicate that the quality of concrete mixtures below 2000 m/s is very poor, those between 2000-3000 m/s are poor, those between 3000-3500 m/s are questionable, those between 3500-4500 m/s are good, and those above 4500 m/s are very good. According to this method, it is understood that all RCC mixtures produced were of at minimum good quality. Similar to the results in this study, Sağlam and Kılıç (2021) found that in their 300 kg and 350 kg dosage samples, the void ratio decreased and UPV values increased as D_{\max} increased.

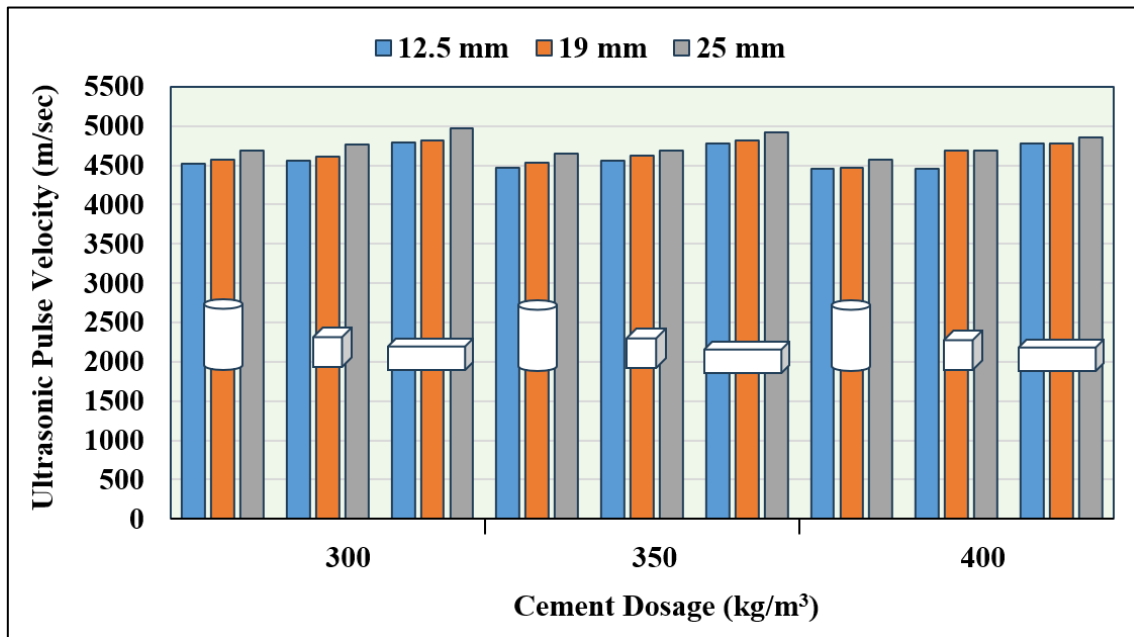


Fig. 12. UPV values of RCC cylinder, cube, and beam specimens.

4. Conclusions

This study investigated the effects of maximum aggregate particle size and gradation on the mechanical and physical properties of RCC pavement mixtures. In this regard, the findings obtained offer significant advantages in the design of RCC pavements in terms of both structural and construction aspects. Higher compressive and flexural strengths can be achieved with the suitable maximum aggregate particle size and gradation selection, while crack formation can be controlled by maintaining tensile strength through the optimum particle size. The high-density microstructure with a low void ratio enhances the durability and long-term performance of the pavement, while the limited variations in unit weight provide additional ease in placement and compaction during field applications. In these respects, the study demonstrates concrete engineering advantages for designing more reliable, durable, and predictable-performance mixtures in RCC pavements. The main findings obtained within the scope of the research are listed below.

- Maximum aggregate particle size and gradation had significant effects on the mechanical properties of RCC pavement mixtures. Increment the aggregate particle size from 12.5 mm to 25 mm resulted in significant increases in compressive and flexural strength. Up to 31% increase in compressive strength and up to 7% increase in flexural strength have been observed.
- Splitting tensile strength increased up to a maximum aggregate particle size of 19 mm, but decreased when reaching 25 mm. While the increase in strength reached up to 17%, decreases of up to 14% were observed with increasing particle size.
- An increment in cement dosage at all levels within the mixtures resulted in a consistent increase in all strength types. Increment of the cement dosage to 350 kg/m³ resulted in average increases of approxi-

mately 8%, 4%, and 2% in compressive, flexural, and splitting tensile strength, respectively. Increment to 350 kg/m³ resulted in increases of 14%, 11%, and 12%, respectively.

- UPV tests revealed that 85% of the mixtures had values above 4500 m/s and showed that the microstructure of the mixtures was dense and the void ratio was low. It has been determined that UPV values increase with an increment in the D_{max} , while they decrease with an increment in cement dosage.
- While both fresh and hardened unit weights of RCC mixtures have similar values, increment in maximum aggregate size has caused a slight increase in unit weights.

Acknowledgements

None declared.

Funding

The author received no financial support for the research, authorship, and/or publication of this manuscript.

Conflict of Interest

The author declares no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Data Availability

The datasets generated and/or analyzed during the current study are not publicly available but are available from the corresponding author upon reasonable request.

AI Assistance

No AI-based tools were used in the preparation of this manuscript.

Author Contributions

The author declares sole responsibility for all aspects of the study, including conceptualization, methodology, formal analysis, investigation, data curation, visualization, writing of the original draft, and writing, review, and editing of the manuscript.

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