



An Experimental and Ultrasonic Pulse Velocity (USPV)-Based Correlation Study on the Influence of Aggregates Gradation on the Flexural Strength of Roller Compacted Concrete (RCC)

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Keywords

Concrete,
Gradation,
Flexural strength,
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Non-destructive testing (NDT),
Roller compacted concrete (RCC),
Ultrasonic pulse velocity (USPV)
correlation.

Abstract

The USPV technique provides a rapid and non-destructive testing (NDT) approach for evaluating concrete pavement quality. It is considered sustainable, safe, quick, and accurate since it does not compromise the structural integrity of the concrete after testing. In the present investigation, RCC slab samples were prepared in the laboratory with three different percentages of ordinary Portland cement and two types of aggregates gradation (dense and gap). Beam specimens were obtained from the compacted slab samples and subjected to flexural strength (FS) determination. Specimens were monitored before and after application of flexural stress with the aid of USPV technique, variations in USPV and FS attributable to aggregate gradation and cement content were quantified and empirically modeled. It was concluded that dense graded RCC mixture shows higher USPV than gap graded mixture by (6.1, 3.2, and 0.9) % for mixtures prepared with (10, 12, and 16) percentages of cement content respectively. The FS of dense graded RCC is higher than that of gap graded RCC by (38.4, 34.7, and 18) % for mixtures prepared with (10, 12, and 16) % cement content respectively. The obtained mathematical power regression models with high coefficient of determination can provide a rough guide and be implemented for fast and preliminary estimation of RCC flexural strength within the investigated material ranges of FS of RCC and instant detection of RCC quality.

1. Introduction

The USPV method of testing concrete is one of the most widely employed and accepted and well-known methods of NDT for concrete assessment. It is thoroughly compared with other well-established NDT approaches and reviewed by Karaiskos et al., 2015, [1] for their principles, reliability, and inherent limitations. In addition, the majority of the current USPV techniques are based on the use of transducers held on the surface of the concrete. Al-Zuhairi, 2013, [2] proposed mathematical expressions for estimating FS of concrete from USPV measurements. Specimens were tested for USPV and FS. Mathematical power regression models were obtained between USPV and FS of concrete. Krishna Rao et al., 2016, [3] presented experimental investigation results of USPV tests conducted on RCC pavement. Relationships between compressive strength (CS), Dynamic Elastic Modulus, and USPV were proposed for the tested concrete mixes.

A new empirical equation was proposed to determine the Dynamic Elastic Modulus of RCC. Toutouchi et al, 2021, [4] evaluated the behavior of RCC as environmentally friendly road pavements using the results of NDT ultrasonic pulse wave velocity test. Several laboratory tests were performed including FS and USPV. It was concluded that there was a good correlation between the findings of USPV values and FS, and it was possible to predict the behavior of RCC samples using this test. Keles and Akpinar, 2022, [5] implemented USPV and rebound hammer tests to determine the physical and mechanical properties of RCC specimens. Rambabu et al., 2023, [6] reviewed the suitability of RCC as a high traffic pavement. The constituents of the RCC mixture concerning their durability, fatigue life, and FS have also been reviewed. Sarsam, 2020, [7] evaluated strength and properties of RCC with the aid of two techniques of NDT testing (USPV, and Schmidt rebound hammer). Slab samples were constructed in the laboratory using roller compactor and subjected to NDT. It was concluded that USPV-based models produced lower FS estimates as compared with Schmidt rebound hammer test. Gouws, 2024, [8] established relationships between CS of RCC used in dam construction with the aid of both (NDT) and destructive testing validated the identified data. Both USPV and Rebound Hammer tests were conducted for each specimen. Following NDT, each specimen was tested for CS test. Regression analysis was conducted with a linear correlation with an excellent R^2 of 93 % which can represent the change in CS which was a function of NDT methods evaluated. Sarsam, 2022, [9] correlated the physical properties of RCC (FS, tensile, and CS) using mathematical models. It was concluded that the CS of RCC was higher than the FS by (3.4 and 2.49) folds for dense and gap graded concrete mixtures respectively. Zárate et al., 2022, [10] validated the relationship of USPV-CS, which allows the resistance of concrete to be determined for a given design of concrete mixtures and determined the most accurate trend and the possibly correct form of the correlation plot between the USPV and uniaxial CS by a logarithmic correlation with a coefficient of determination greater than that of the linear trend, was obtained. The viability of NDT methods for finding out the mechanical properties of concrete was evaluated by Roobankumar, and SenthilPandian, 2025, [11].

The study established a correlation between CS and USPV tests to predict the CS of concrete using USPV test results. The empirical relationships between CS and USPV were found to be exponential, with high correlation values. Moutassem and Kharseh, 2024, [12] proposed mathematical model based on nonlinear regression to predict the CS of concrete accurately based on USPV measurements and outline the proposed models' calibration, formulation, validation and evaluation through an experimental program. Analysis of the results reveals the significant fit of the proposed nonlinear regression model to the experimental data. The model exhibited exceptional accuracy, attained high coefficients of

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determination, and effectively predicted CS values. An experimental study was performed by Choi et al., 2022, [13] on the strength properties of concrete using destructive and NDT tests. USPVP tests were used to evaluate the strength property of concrete as an NDT test. Splitting tensile and CS were determined for concrete, and exponential equations were proposed for the relationship between splitting tensile, CS and the USPVP of concrete. It was concluded that USPVP tests could also be used to estimate the tensile and CS of concrete. Sethi et al., 2024, [14] estimated the CS of RCC with the aid of appropriate mathematical formulas based on NDT findings. This was accomplished by preparing and testing many RCC samples using NDT methods including USPVP, as well as traditional concrete breaking tools. Appropriate relations were obtained using the values from both destructive and NDT tests. It was concluded that the RCC CS can accurately be determined using the suggested relations by conducting NDT testing instead of destructive testing. Sarsam, 2021, [15] prepared RCC slab samples with dense and gap graded aggregates. Cube specimens were obtained from the slab samples and tested for USPVP in two different positions, parallel and perpendicular to the rolling direction. It was concluded that dense graded mixture exhibits higher USPVP traversing perpendicular to the direction of rolling, while gap graded mixtures show higher USPVP traversing parallel to the rolling direction. Handika et al., 2020, [16] presented a series of experiments to investigate homogeneity and to predict the CS of concrete using NDT and Destructive tests. USPVP propagation measurements through vertical prismatic beam specimens were performed. Concrete specimens were tested under compression. The USPVP through the concrete and its CS relationship demonstrated exponential power regression pattern. It was concluded that such pulse velocity-concrete strength relationships may be implemented to predict the strength of concrete. Brožovský, 2009, [17] presented the evaluation of correlations for calculation of concrete CS using NDT parameters for USPVP method. It was concluded that calculation of correlation based on USPVP implies is not significant without specifying a range of its validity regarding the wave velocity. Samanasa et al., 2024, [18] conducted an assessment on RCC paving mixture using USPVP technique. The FS, tensile, compressive, dynamic elastic modulus, and USPVP values were determined. It was noticed that USPVP values increased considerably with curing time. Empirical relationships were proposed between Dynamic Elastic property, strength, and USPVP of concrete in terms of curing age. It can be revealed from the above literature review that most studies focused on CS and not FS of RCC. However, limited studies isolated aggregate gradation effects under controlled RCC compaction.

The aim of the present investigation is to detect the Impact of aggregates gradation and cement content on the FS property of RCC with the aid of USPVP technique with specific emphasis on isolating aggregate gradation effects under identical compaction and curing conditions. Slab samples of roller RCC were prepared with dense and gap aggregates gradation and variable cement content and subjected to USPVP determination. Beam specimens were obtained from the slab samples and tested for FS. Data are analyzed, and the impact of cement content and gradation type are modeled and used for preliminary prediction of the quality of RCC.

2. Materials and Methods

2.1. Portland cement

Ordinary Portland cement with a commercial name of (Tasluga, Al-Jesser) was implemented in this investigation. The physical properties and chemical composition of the Portland cement comply with the technical specification of IQS No. 5, 1984, [19]. The Specific surface area, Blain method is 357 m²/Kg and the C₃S content is 35 %. More details of the Portland cement properties could be referred to Sarsam, 2022, [9].

2.2. Coarse and fine aggregates

Crushed gravel with a nominal maximum size of (25 mm) was sourced from Nibae region while the fine aggregates were sourced from Al-Ukhaider and implemented in this work. The aggregates were separated into different sizes by sieving. The physical properties of aggregates are shown in Figure 1. The test was conducted according to ASTM (C-127), 2001, [20] and ASTM (C-128), 2001, [21].

2.3. Combined gradation of coarse and fine aggregate

Dense gradation usually used for asphalt concrete pavement base course in Iraq with 25 mm of nominal maximum size of aggregates as per SCRB-R-9, 2003,[22] and Gap gradation usually recommended by BS, 1961, [23] have been adopted for this investigation. The gap gradation has also 25 mm maximum size aggregate as a center line of British Standards B.S. 1961. Figure 2 exhibits their combined aggregates gradation. The fines content (passing sieve No. 200 is 7% for both gradation types.

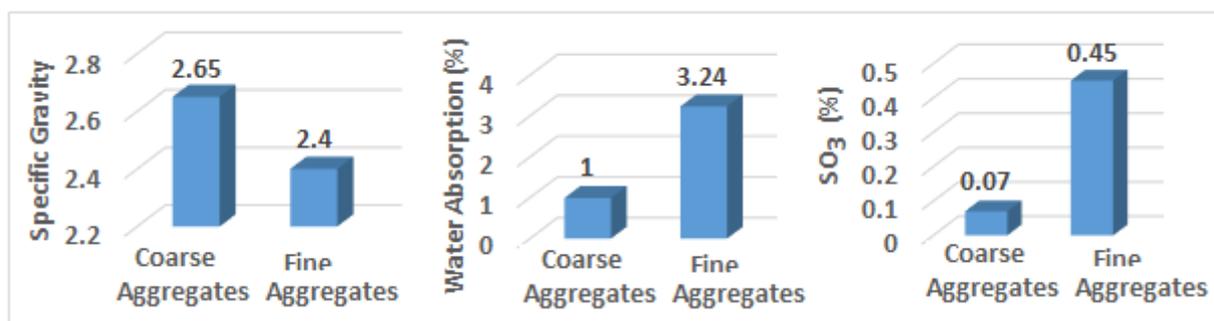


Figure 1. Properties of coarse and fine aggregates

2.4. Mix Design of roller compacted concrete

Modified compaction of the cement-aggregate mixture was conducted according to ASTM-D1557-2002, [24] which is valid also for RCC mixture design and the maximum dry density and optimum moisture content was obtained. Various percentage of water content with a range of (11–4) % of air-dry aggregate with 1% increment were added. Five different percentages of Portland cement content were used (18, 16, 14, 12, and 10) % by weight of air-dry aggregate to construct the dry density-moisture content relationships. Details on the mixture density are published elsewhere at Sarsam et al., 2012, [25]. Table 1 exhibits the quantities of materials implemented in the preparation of the RCC specimens.

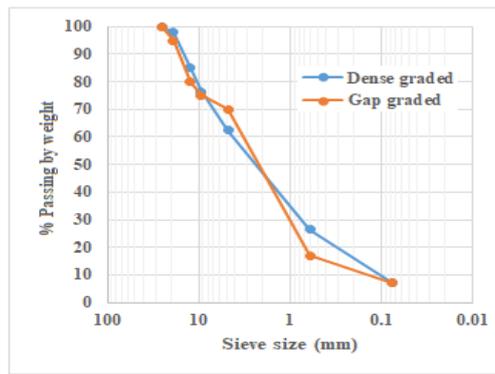


Figure 2. Implemented gradation of aggregates

Table 1. Quantities of materials adopted

| Gradation | Material | Mixing weight(gm) |
|-----------|------------------|-------------------|
| Dense | Cement | 287 |
| | Water | 144 |
| | Fine aggregate | 635 |
| | Coarse aggregate | 1760 |
| Gap | Cement | 282 |
| | Water | 164 |
| | Fine aggregate | 400 |
| | Coarse aggregate | 1947 |

2.5. Preparation of RCCP samples

The water used in RCC mixes was tap water. This water was also used for curing. The designed water-cement-aggregates mixture was placed in a slab mold with size (100× 380 × 380) mm and subjected to initial compaction of three cycles of (8 seconds) vibration of 50 Hz frequency on a vibrating table with a rest period of 30 seconds, then the mold was fixed in front of the laboratory roller compactor device and subjected to three stages of rolling based on the work done by Sarsam, 2020, [26] and Abdulrahim 2011, [27]. For each stage,10 passes were applied and the rolling action is taken in (y-y) direction, then repeated in the (x-x) direction as shown in Figure 3. The total load of the three rolling stages was (1.1, 3.2, and 5.3) kg/cm-width respectively which was applied with 10 roller passes in each direction. Such loading sequence may represent the three rolling processes adopted in the field (initial, breakdown, and finishing) rolling pattern. A limited six slab samples of RCC were prepared which may be implemented to preliminary prediction within the material ranges investigated of the FS of RCC based on NDT by USPV technique. The samples were covered with polyethylene sheet and left to set at laboratory temperature of 30±2°C for 24 hours. The slab samples were removed from the mold and cured in the water bath for (28) days at 25±2°C. Figure 4 exhibits part of the cast RCC slab samples. Three beam specimens of (100×380×80) mm were obtained from each slab samples with the aid of diamond saw. Such beam specimens were treated as independent triplicates. A total of 18 beam specimens were obtained and tested in triplicate; the average value of the test was considered for analysis. The accepted standard deviation was 5 % for the testing results for such a limited testing program. Raw data was obtained from Sarsam et al., 2013, [28]. New analysis, interpretation of data, and new modelling were conducted in this work as preliminary empirical relationships.

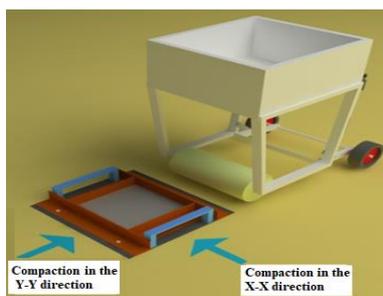


Figure 3. Roller compaction apparatus



Figure 4. Part of the RCC slab samples

2.6. Testing for active UPS with Pundit

The active UPS technology was adopted to measure the USPV with the aid of PUNDIT according to ASTM C-597, 2002, [29]. The pundit with frequency 55KHz and accuracy of 0.1, was implemented to measure the USPV through RCC beam specimens. The implemented PUNDIT is shown in Figure 5. Measurements of active USPV were conducted on beam specimens in a position parallel to the rolling direction as demonstrated in Figure 6.



Figure 5. USPV measuring apparatus



Figure 6. Measurement of active USPV on beams

2.7. Testing for FS

The obtained beam specimens were tested for FS using simple beam with center point loading according to ASTM C293-2003, [30].

3. Results and Discussion

The literature offers concrete categories defined in dependence on UPS as reported by Brožovský, 2009, [17]; Al-Zuhairi, 2013, [2]; Toutounchi et al., 2021, [4]; Samanasa et al., 2024, [18], and presented in Table 2. In general, both aggregate gradations exhibit good RCC mixtures from USPV point of view. Such information exhibits a rough guide of quality of the prepared conventional concrete mixtures although they do not represent the specific RCC mixture. However, the impact of higher and lower paste content in case of RCC was monitored after preparation of extra samples with higher and lower cement content than the optimum requirements of cement using (10, and 16) % of cement while the optimum cement content was 12 %.

Table 2. Typical USPV values range from literature

| USPV (mm/microseconds) | Condition |
|------------------------|----------------|
| Below 2.130 | Very poor |
| 2.130 to 3.050 | Generally poor |
| 3.050 to 3.660 | Questionable |
| 3.660 to 4.570 | Generally good |
| Above 4.570 | Excellent |

Figure 7 exhibits the influence of aggregates overall gradation on the USPV through concrete beam specimens prepared with various cement content before testing for FS. Eight transmission readings were performed and averaged for each of the triplicate specimen. A sharp increase in the USPV trend is detected as the cement content increases regardless of aggregates gradation type. Dense graded mixture shows a higher USPV than the gap graded mixture by (6.1, 3.2, and 0.9) % for mixtures prepared with (10, 12, and 16) % cement content respectively. Such decline in the variation in USPV between dense and gap gradation when the cement content rises may be related to the possible decline in the voids content due to hydration and increase in the density of the mixture. The rate of increase in the USPV as the cement content rises is sharper for gap graded mixture than that of dense graded mixture as shown in Table 2. Toutounchi et al, 2021,[4] reported similar behavior.

Table 3 exhibits mathematical power regression models which correlate the USPV with cement content for both gradations of aggregates. The intercept (representing the base USPV) of the dense gradation mixture is higher than that of gap gradation mixture by 38 %, while the slope (which represents the rate of increase of the USPV) of the dense gradation is lower than that of gap gradation by 33.8 %. Both models show high (R²) coefficients of determination. Al-Zuhairi, 2013, [2]; and Handika et al., 2020, [16] reported similar type of models. Due to the limited number of tested specimens, high R² exhibits empirical nature and limited domain. Such models are considered as preliminary empirical relationships.

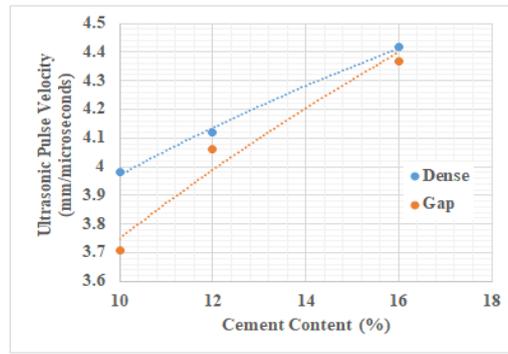


Figure 7. Influence of aggregates overall gradation on the USPV

Table 3. Mathematical models of the influence of aggregates overall gradation on the USPV

| Gradation type | Intercept | Slope | Mathematical model | Coefficient of determination |
|----------------|-----------|-------|--------------------------|------------------------------|
| Dense | 2.3649 | 0.225 | $Y = 2.3649 X^{(0.225)}$ | 0.9969 |
| Gap | 1.7139 | 0.340 | $Y = 1.7139 X^{(0.34)}$ | 0.9662 |

Y = USPV (mm/microseconds); X = Cement content (%)

Figure 8 demonstrates the FS-cement content relationship for both aggregates' gradation. The FS increases as the cement content rises regardless of the gradation type. Eight transmission readings were performed and averaged for each of the triplicate specimen. Dense gradation exhibits higher FS than gap gradation for the assessed cement content. However, such variation declines at higher cement content. The FS of dense graded RCC is higher than that of gap graded RCC by (38.4, 34.7, and 18) % for mixtures prepared with (10, 12, and 16) % cement content respectively.

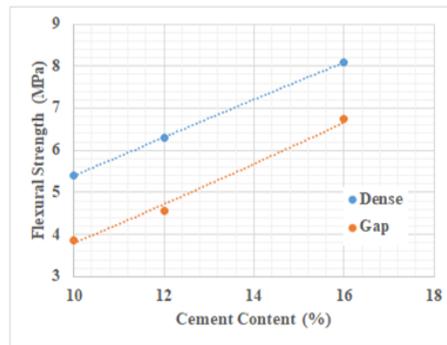


Figure 8. Influence of aggregates overall gradation on the FS

Table 4 presents the mathematical power regression models of the FS-cement content relationship for both gradation types. The intercept of dense aggregates gradation is higher than that of the gap graded aggregates by 207 %, while the slope of dense mixture is lower than that of gap mixture by 28 %. Higher coefficients of determination indicate strong relationships. However, due to the limited number of tested specimens, high R² exhibits empirical nature and limited domain. Such models are considered as preliminary empirical relationships.

Table 4. Mathematical models of the influence of aggregates overall gradation on the FS

| Gradation type | Intercept | Slope | Mathematical model | Coefficient of determination |
|----------------|-----------|--------|---------------------------|------------------------------|
| Dense | 0.7382 | 0.8637 | $Y = 0.7382 X^{(0.8637)}$ | 0.9999 |
| Gap | 0.2399 | 1.1991 | $Y = 0.2399 X^{(1.1991)}$ | 0.9925 |

Y = FS (MPa); X = Cement content (%)

Figure 9 exhibits the relationship between USPV and FS of RCC for both gradations of aggregates. Eight transmission readings were performed and averaged for each of the triplicate specimen. Higher USPV and FS are associated with dense graded RCC as compared with gap graded RCC mixture.

Table 5 presents the mathematical power regression models between USPV and FS of RCC. The intercept of dense graded mixture is lower than that of gap graded mixture by 40 % while the slope of dense graded mixture is higher than that of gap graded mixture by 142 %. Both models exhibited high coefficients of determination. Due to the limited number of tested specimens, high R² exhibits empirical nature and limited domain. Such models are considered as preliminary empirical relationships.

Table 5. Mathematical models of the USPV-FS relationship

| Gradation type | Intercept | Slope | Mathematical model | Coefficient of determination |
|----------------|-----------|--------|---------------------------|------------------------------|
| Dense | 0.0277 | 3.8241 | $Y = 0.0277 X^{(3.8241)}$ | 0.9973 |
| Gap | 0.0465 | 3.3401 | $Y = 0.0465 X^{(3.3401)}$ | 0.9296 |

Y = FS (MPa); X = USPV (mm/microseconds)

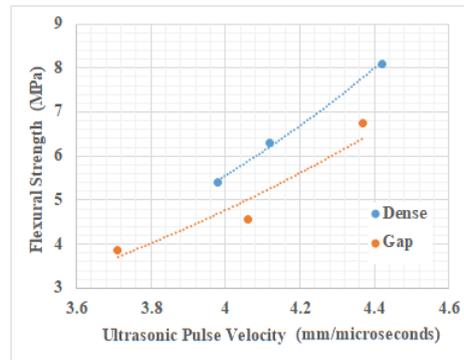


Figure 9. USPV-FS relationship

4. Conclusions

Based on the limited testing program, limited sample size, laboratory-scale applicability, need for field validation, and the properties of raw materials, the following conclusions are drawn.

Dense graded mixture shows higher USPV than gap graded mixture by (6.1, 3.2, and 0.9) % for mixtures prepared with (10, 12, and 16) % cement content respectively. The FS of dense graded RCC is higher than that of gap graded RCC by (38.4, 34.7, and 18) % for mixtures prepared with (10, 12, and 16) % cement content respectively. The obtained mathematical power regression models exhibited high coefficients of determination and may be implemented to preliminary prediction within the material ranges investigated of the FS of RCC based on NDT by USPV technique. However, due to the limited number of tested specimens, high R^2 exhibits empirical nature and limited domain.

Declaration of Conflict of Interests

The author declares that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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