Dynamic modulus of elasticity and compressive strength evaluations of modified reactive powder concrete (MRPC) by non-destructive ultrasonic pulse velocity method

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ABSTRACT

This study investigates the method of ultrasonic pulse velocity technique as a non-destructive test for concrete to estimate the mechanical properties of RPC, modified reactive powders concrete (MRPC). This study is based on data obtained from the experimental investigation done in this work and comparison with the data of previous works. After conducting pulse velocity tests on cubic samples, the relationship between pulse velocity, elastic modulus and compressive strength of samples was obtained with an acceptable approximation. Also, the validity of the proposed relation ACI 363.1 and four distinguished researchers regarding the calculation of RPC, MRPC elastic modulus and its comparison with the dynamic elasticity modulus (ASTM C 597) with respect to different materials and mix designs. The dynamic modulus of elasticity (Ed) increased on average by 19% over the modulus of elasticity (Ec). Given the lack of research on the relationship between the parameters mentioned in the MRPC, the present study is an exploratory research concerned with the relationship of these methods. Also, two new models are presented for relating these parameters.

1. Introduction

System is a collection whose components interact with each other and are interconnected in different ways. Components do a common function towards an input to produce an output. The components and systems are developed under certain limiting factors in the surrounding area. The system components function in the form of systems and subsystems of a system which are higher. In light of this attitude, the concrete comprises a living system with a series of three general sub-systems, aggregate sub-system, cement paste sub-system (cement, water and air bubbles, chemical additives) and interface zone sub-system; all in the total larger systems will create a synergy (Ahmadvand and Moghaddam 2006).

Indeed, the relationship between the components (individually) in a system is more important than the system components themselves. In this study, we tried a new approach by utilizing two opposite concepts with a systematic view and focus on aggregate-cement paste connecting area, on which superplasticizer exerts its effect. This approach introduces the field of employing new materials in the form of concrete science (Moghaddam 2008, 2014; ACI 238.1R-08).

Reactive powder concrete (RPC) is a relatively new type of ultra-high-performance concrete developed by Richard and Cheyrezy in the early 1990s. RPC is composed of Portland cement and ultra-fine powders such as crushed quartz and silica fume. Compared to ordinary cement-based materials, the primary improvements of RPC are related to particle size homogeneity, porosity, and microstructure. A highly dense matrix is achieved by optimizing the granular packing of these powders. RPC is achieved by a microstructural engineering approach including eliminating the coarse aggregates, reducing the water-cementitious material ratio (w/cm), lowering the CaO/SiO₂ ratio by introducing silica components, and incorporating steel microfibers (Aydin and Baradan 2013; Raza et al. 2020; Grzeszczyk et al. 2020; Sobuz et al. 2016; Kushartomoa, Balib, and Sulaimana 2015; Grzeszczyk and Janusab 2020; Najim Abbas, Abdulzahra, and Qasim 2016; Grzeszczyk et al. 2018; Salman, Al-Rumaithi, and Al-Sherrawi 2018; Zhang et al. 2018; Wang et al. 2018; Abid et al. 2017).

As new types of concrete appear, further investigation for their mechanical properties is needed, one of these types is the reactive powder concrete as a type of ultra-high performance concrete having a dense and durable composite mix generally characterized by low water/cement ratio, high cement content (Bae et al. 2016).

There were 90 specimens fabricated for this research with strength values ranging from 7 MPa to over 37 MPa. A stress wave propagation-based
technique such as the UPV test will provide a more reliable estimate of the in-place strength compared with the rebound hammer test. However, the residual analysis shows that for higher-strength concrete, the UPV test is less reliable (Sajid et al. 2016).

The UPV test appears to be better suited for this purpose in developing countries, given its ease of use, compact equipment and minimal amount of data analysis. It may however not be as reliable and robust as the resonant frequency test and the factors affecting UPV test results must be taken into account when using it for strength estimation (Sajid et al. 2017).

The RPC appears to have linear-elastic, isotropic properties within some limits. It is possible to use this characteristic to estimate elastic properties of the material, and there was close correlation with statically measured properties in the small number of specimens tested. Additional testing is required to provide affirmative evidence that ultrasonic wave velocities can be used to determine elastic properties for engineering purposes, but the potential for that to be true has been established (Washer et al. 2004).

Only ultrasonic techniques were used to determine to ultrasonic pulse velocity (direct transmission), according to EN 12054–4. The main influencing parameters on the output of the UPV are the type, content and hardness of the aggregates, the presence of cracks/voids in the structure and the moisture content of the concrete. However, although these methods are simple and effective, NDT produces different results depending on the formula applied (Denys 2012).

Investigation is to apply refinements in RPC by introducing graded aggregate into it (3–8 mm) so as to make this RPC more economical and feasible without much reduction in its mechanical properties. This modification makes the traditional RPC as an innovative MRPC (Modified Reactive Powder Concrete) (Sujatha and Basanthi 2014).

The ultrasonic pulse velocity technique, which is based on calculating the ultrasonic pulse transfer velocity in concrete, is one of the non-destructive testing methods that can be used to help estimate the characteristics of concrete members (Sabbagh and Uyanik 2017). The homogeneous nature of RPC results in a more linear elastic behavior, less scattering and more easily propagated ultrasonic waves. Based on the results, it was concluded that RPC demonstrated essentially isotropic elastic properties when measured by an ultrasonic pulse (Washer, Fuchs, and Graybeal 2003). An additional problem when calculating the compressive strength of concrete using the impulse excitation method is the difference between the static and dynamic modulus of elasticity of concrete. The studies clearly show that the dynamic modulus is significantly greater than the static one (Jurowski and Grzeszczuk 2018; Sabbagh and Uyanik 2018).

Elastic modulus of concrete $E_c$ can be determined by dynamic test methods such as ultrasonic pulse velocity and resonance frequency tests. The resulting elastic modulus is commonly referred to as dynamic elastic modulus $Ed$, which is larger than static elastic modulus $Ec$. The dynamic elastic modulus is generally 20%, 30%, and 40% higher than the static elastic modulus for high, medium, and low-strength concrete, respectively (Mehta and Monteiro 1993). There are several empirical equations that relate $Ed$ and $Ec$. Lydon and Balendran proposed the following empirical relationship between $Ed$ and $Ec$:

$$Ec = 0.83Ed(GPa)$$  \hspace{1cm} (1)

The British testing standard BS8100 Part 2 provides another empirical equation for $Ec$ as follows:

$$Ec = 1.25Ed - 19(GPa)$$  \hspace{1cm} (2)

It is noteworthy that this equation does not apply to concrete containing more than 500 kg of cement per cubic meter of concrete or to lightweight aggregate concrete.

However, it should be mentioned that additional experimental data should be accumulated to better understand the size effect on the relationship between static and dynamic elastic moduli of high-strength concrete (>60 MPa) due to scarcity of experimental studies in such a high-strength range (Lee et al. 2015).

Accordingly, in this research we have tried to determine the performance of this non-destructive test method for RPC, MRPC, and to find the relationship between compressive strength and ultrasonic pulse transfer velocity from an RPC, MRPC sample. In addition, the focus of research is on providing relationships between them and comparing the elastic modulus of elasticity with the dynamic elasticity modulus.

2. Research significance

The relationship between pulse velocity and modulus of dynamic elasticity and compressive strength of RPC, MRPC, and proposed new models were also investigated.

Comparison between the dynamic modulus of elasticity and the results of previous studies on the static modulus of elasticity was also performed and the mean of the obtained results was evaluated.

This research could lead to the development of application of RPC, MRPC and the use of pulse velocity in determining the compressive strength and dynamic modulus of elasticity to reduce the time and cost for sustainable development.

3. Previous provisions

3.1. Modulus of elasticity

Over the years, several researchers have tried to estimate the mechanical properties of concrete such as modulus of elasticity, As the concrete manufacturing
evolved for producing new types of concrete, new formulas were proposed to simulate the new types of concrete.

Regarding ACI 363 R elasticity concrete, there is a correlation between the modulus of elasticity $Ec$ and the compressive strength $f’c$ for normal weight concretes Equation (3):

$$ Ec = 3320(f’c)^{0.5} + 6900 \text{ MPa for } 21 \text{ MPa} < f’c < 83 \quad (3) $$

As the knowledge about the reactive powder concrete increased, Al-Hassani, Khalil, and Danha (2013) tried to give a better estimation for the modulus of elasticity based on regression analysis as in Equation (4):

$$ Ec = 113.43 f’c + 31126.74 \quad (4) $$

The proposed equation (Equation (5)) was found to be more suitable and representative for reactive powder concrete behavior and be more reflective of its components’ properties adopting a new power for the compressive strength of 0.25 (Kadhem et al. 2018):

$$ Ec = 14000(f’c)^{0.25} \quad (5) $$

For both normal strength and high-strength concrete, the Comite-Euro-International (CEB-FIP) Model code and Eurocode 2 suggest an empirical equation (Equation (6)) relating $Ec$ and $f’c$ as follows (Lee et al. 2015):

$$ Ec = 22000 \left( f’c / 10 \right)^{1/3} (\text{MPa}) \quad (6) $$

A practical equation proposed by Noguchi et al. (Kadhem et al. 2018) (Equation (7)), which was developed based on an extensive experimental database from normal to high-strength concrete:

$$ Ec = k_1 k_2 33500( f’c / 60)^{1/3} (\rho / 2400)^2 \quad (7) $$

By addressing correction factors for the effects of aggregates and mineral admixtures (in this paper used Crushed quartzitic aggregate and Silica fume 10%–20%) So according to Table 3 of Kadhem et al. (2018) $k_1 = 1$, $k_2 = 0.956$ included in the calculations.

### 3.2. Poisson’s ratio

ACI 363 R reported values for Poisson’s ratio of normal weight high-strength concretes with compressive strengths ranging from 8000 to 11,600 psi (55 to 80 MPa) between 0.20 and 0.28. They concluded that Poisson’s ratio tends to decrease with increasing water-cement ratio. Kaplan (1959) found values for Poisson’s ratio of concrete determined using dynamic measurements (Simmons 1955; Ahmed 2018) to be from 0.23 to 0.32 regardless of compressive strength, coarse aggregate, and test age for concretes having compressive strengths ranging from 2500 to 11,500 psi (17 to 79 MPa).

Aydin and Baradan (2013) also obtained Poisson’s ratio RPC in a reliable study (Steam curing 100°C [212°F], 12 hours and Standard curing, 28 days) of 0.21, which research is based on the calculation of this number.

### 4. Experimental procedure

#### 4.1. Material and mixture proportion

A total of 77 concrete mixtures (30 Mixtures were selected based on the results of the ready mixed concrete test) were used throughout this investigation. These concrete mixtures were made in the “Concrete Research and Education Center (ConREC)” affiliated with ACI (American Concrete Institute Iran Chapter). According to ASTM C 150 type II, V Portland cement (ASTM C-150-15 2015) was used for all of the concrete mixtures. A commercial silica fume was also used in this study. BET fineness (Brunauer, Emmett and Teller) the specific surface area and specific gravity of silica fume were 23,360 m²/kg and 2100 kg/m³, respectively. The chemical compositions of the colloidal and powder nano-silica and silica fume (ASTM C 1240-18 2018) are also presented in Table 1. Commercial quartz sand, in three different size fractions (75 µm to 6 mm, 0 to 1 mm, and 0 to 75 µm) as well as natural sand and gravel in four different size proportions (0 to 75 µm, 0 to 5 mm, 5 to 9.5 mm and 9.5 to 19 mm) were used as aggregate. The gravel was added by replacing quartz sand in SCC and traditional concretes.

Chemical characteristics of quartz sand and silica fume are shown in Table 2. For all normal concretes, coarse aggregates were crushed into calcareous stone with a maximum size of 19 mm and fine aggregates were natural sand. The coarse aggregates had a specific gravity and water absorption of 2550 kg/m³ and 1.10%, respectively, while the fine aggregate had water absorption of 2.25% and a specific gravity of 2585 kg/m³.

For a polycarboxylate-based high-range water-reducing admixtures (HRWRA) complying with ASTM C494 Type F (ASTM C494/C494M-08 2008), the specific gravity and solid content of the HRWRA was 1050 kg/m³ and 40%, respectively.

| Table 1. Properties of colloidal, powder nano silica and silica fume. |
|---------------------------------------------------------------|
| **Type** | **SiO₂ (%)** | **size (nm)** | **SP.SurfaceArea (m²/g)** | **salt content (%)** | **Density (kg/m³)** |
| Colloidal nano silica | 99.9 | 35 | 400 | 24 | Combiner | 1.05 |
| Powder nano silica | 99 | 20–30 | 160–200 | 100 | powder | 0.150–0.220 |
| Silica Fume | 90 | 229 | 20.7 | 100 | powder | 2.1 |
Potable water was used for casting all concrete specimens. Limits and limitations of mixing designs include water to cement ratio and cement content as well as aggregate ratio. According to the results of past research (Aydin and Baradan 2013; Raza et al. 2020; Grzeszczzyk et al. 2020; Sobuz et al. 2016; Kushartomoa, Balib, and Sulaimana 2015; Grzeszczyk and Janusab 2020; Najim Abbas, Abdulzahra, and Qasim 2016; Grzeszczzyk et al. 2018; Salman, Al-Rumaihith, and Al-Sherrawi 2018; Zhang et al. 2018; Wang et al. 2018; Abid et al. 2017) and Results from 77 initial designs were selected and finalized. The mixture proportions for concrete specimens consist of 22 mixing designs RPC, MRPC and Five SCC mix designs and three ordinary concrete mix designs as shown in Table 3.

4.2. Testing procedure and specimen preparation

4.2.1. Pulse transfer velocity

In this study, the compressive strength and pulse velocity test device of Reactive Powder Concrete (RPC) with Modified Reactive Powder Concrete (MRPC) and Self Compacting Concrete have been compared with different proportions of aggregates and varying sizes. The strengths have been tested after usage at 3, 7, 28 and 90 days by curing according to ASTM C 33 and accelerated curing of 24 hrs at 80°C. The specimens cube of sizes 150x150x150mm are for Chosen mix design.

On 28-day cubic samples, a non-destructive test was carried out to determine the transfer time of the ultrasonic pulse by direct method via a pulse velocity test device. The P-wave velocity of concrete was measured according to ASTM C 597 (ASTM C 597-16 2016) using a pair of P-wave transducers (see Figure 1), each of which generates and receives a longitudinal ultrasonic pulse. The manner in which this test was performed is shown in Figure 1. The frequency was sent from the device at 54 KHz and the duration of the pulse transfer in μs and with an accuracy of 0.1 μs was displayed on the digital screen of the devices. In all experiments, refractory grease was used to connect the transducers to the concrete surface; before the test, the surface under test was flat. On each sample, readings were taken from the pulse travel time at different points of the concrete surface, until almost all of the sample surfaces and, therefore, the entire sample volume was tested. After completing the test by collating the results, a number was recorded as the pulse transfer time and pulse transient. This number was calculated from Equation (8), in kilometers per second, given that the length of the path was 15 cm.

\[ V = \frac{L}{T} \]  

(8)

Where, V represents the gain in pulse transfer velocity (km/s); L is length of the path (km), and T is duration of the pulse transfer (s).

4.2.2. Dynamic modulus of elasticity

In the ASTM C 597 (ASTM C 597-16 2016) standard, a formula is presented which uses a pulse velocity, Poisson’s ratio and concrete unit weight to obtain the modulus of the dynamic elasticity of the concrete Equation (9) is as follows.

\[ E_d = \rho \nu^2 \frac{(1 + \mu)(1 - 2\mu)}{(1 - \mu)} \]  

(9)

After performing non-destructive tests on concrete samples, the specimen was tested under compressive strength test measured in MPa. Figures 2-4 show some graphs after these tests.

5. Results and discussions

The results obtained from the pulse velocity test and the compressive strength of cubic samples on 28 days according to (BS EN 12390-3 2019) and modulus of elasticity are presented in Table 4.

As can be seen in Figure 5, there is a relationship between pulse velocity and compressive strength established by nonlinear regression analyses (\( R^2 = 0.9001 \)) of the concrete in RPC, MRPC. The dynamic modulus of elasticity was calculated from both the prescribed Equation (9) of ASTM C 597 and the proposed Equations (3)-(7) which was also compared. As can be seen in Figure 6, excellent relationships have been obtained between dynamic modulus of elasticity Equation (9) and compressive strength with the RPC and MRPC (\( R^2 = 0.9021 \)).

The comparison of static and dynamic elastic modulus of concrete mix designs for all formulas (Figure 7). An average of about 19% of the results obtained from the determination of the dynamic modulus of elasticity (Ed) higher than with the proposed formulations of the researchers (Ec) was obtained (Figure 8).

Finally, considering the obtained correlations, two new models for correlating compressive strength with pulse velocity and dynamic modulus of elasticity are presented in Table 5.

| Table 2. Chemical compositions (%) of quartz sand and silica fume. |
|----------------------|------------------|------------------|------------------|------------------|------------------|
|                     | SiO₂             | Al₂O₃            | Fe₂O₃            | CaO              | Na₂O            |
| Quartz Sand         | 96–98.8          | 0.151–1.65       | 0.2–0.7          | 0.2–0.5          | 0.03–0.08       |
| Silica Fume         | 90               | 1.3              | 1.1              | 1.7              | 0.5             |
|                     | k₂O              |                  |                  |                  | 0.03–0.1        |
| No. | Mixtures                     | Concrete seventh | Spec. Dice | Mixture Type | Water (kg/m³) | PCE (kg/m³) | Sand (0 to 3 mm), kg/m³ | Quartz (0 to 1.75 mm), kg/m³ | Quartz (75 µm to 315 µm), kg/m³ | Colloidal Nano Silica (kg/m³) | Silica Fume (kg/m³) | Powder Nano Silica (kg/m³) | CMC (g/L) |
|-----|------------------------------|------------------|------------|--------------|--------------|-------------|------------------------|------------------------------|---------------------------------|------------------------|----------------------|------------------------|-------------|
| 1   | 5 169                       | 58               | 0.35        | SCC          | 165          | 18          | 0.045                  | 0.045                        | 0.045                           | 0.045                 | 0.045                | 0.045                  | 0.45        |
| 2   | 6 170                       | 58               | 0.35        | SCC          | 165          | 18          | 0.045                  | 0.045                        | 0.045                           | 0.045                 | 0.045                | 0.045                  | 0.45        |
| 3   | 7 171                       | 58               | 0.35        | SCC          | 165          | 18          | 0.045                  | 0.045                        | 0.045                           | 0.045                 | 0.045                | 0.045                  | 0.45        |
| 4   | 8 172                       | 58               | 0.35        | SCC          | 165          | 18          | 0.045                  | 0.045                        | 0.045                           | 0.045                 | 0.045                | 0.045                  | 0.45        |
| 5   | 9 173                       | 58               | 0.35        | SCC          | 165          | 18          | 0.045                  | 0.045                        | 0.045                           | 0.045                 | 0.045                | 0.045                  | 0.45        |
| 6   | 10 174                      | 58               | 0.35        | SCC          | 165          | 18          | 0.045                  | 0.045                        | 0.045                           | 0.045                 | 0.045                | 0.045                  | 0.45        |
| 7   | 11 175                      | 58               | 0.35        | SCC          | 165          | 18          | 0.045                  | 0.045                        | 0.045                           | 0.045                 | 0.045                | 0.045                  | 0.45        |
| 8   | 12 176                      | 58               | 0.35        | SCC          | 165          | 18          | 0.045                  | 0.045                        | 0.045                           | 0.045                 | 0.045                | 0.045                  | 0.45        |
| 9   | 13 177                      | 58               | 0.35        | SCC          | 165          | 18          | 0.045                  | 0.045                        | 0.045                           | 0.045                 | 0.045                | 0.045                  | 0.45        |
| 10  | 14 178                      | 58               | 0.35        | SCC          | 165          | 18          | 0.045                  | 0.045                        | 0.045                           | 0.045                 | 0.045                | 0.045                  | 0.45        |
| 11  | 15 179                      | 58               | 0.35        | SCC          | 165          | 18          | 0.045                  | 0.045                        | 0.045                           | 0.045                 | 0.045                | 0.045                  | 0.45        |
| 12  | 16 180                      | 58               | 0.35        | SCC          | 165          | 18          | 0.045                  | 0.045                        | 0.045                           | 0.045                 | 0.045                | 0.045                  | 0.45        |
| 13  | 17 181                      | 58               | 0.35        | SCC          | 165          | 18          | 0.045                  | 0.045                        | 0.045                           | 0.045                 | 0.045                | 0.045                  | 0.45        |
| 14  | 18 182                      | 58               | 0.35        | SCC          | 165          | 18          | 0.045                  | 0.045                        | 0.045                           | 0.045                 | 0.045                | 0.045                  | 0.45        |
| 15  | 19 183                      | 58               | 0.35        | SCC          | 165          | 18          | 0.045                  | 0.045                        | 0.045                           | 0.045                 | 0.045                | 0.045                  | 0.45        |
| 16  | 20 184                      | 58               | 0.35        | SCC          | 165          | 18          | 0.045                  | 0.045                        | 0.045                           | 0.045                 | 0.045                | 0.045                  | 0.45        |
| 17  | 21 185                      | 58               | 0.35        | SCC          | 165          | 18          | 0.045                  | 0.045                        | 0.045                           | 0.045                 | 0.045                | 0.045                  | 0.45        |
| 18  | 22 186                      | 58               | 0.35        | SCC          | 165          | 18          | 0.045                  | 0.045                        | 0.045                           | 0.045                 | 0.045                | 0.045                  | 0.45        |
| 19  | 23 187                      | 58               | 0.35        | SCC          | 165          | 18          | 0.045                  | 0.045                        | 0.045                           | 0.045                 | 0.045                | 0.045                  | 0.45        |
| 20  | 24 188                      | 58               | 0.35        | SCC          | 165          | 18          | 0.045                  | 0.045                        | 0.045                           | 0.045                 | 0.045                | 0.045                  | 0.45        |
| 21  | 25 189                      | 58               | 0.35        | SCC          | 165          | 18          | 0.045                  | 0.045                        | 0.045                           | 0.045                 | 0.045                | 0.045                  | 0.45        |
| 22  | 26 190                      | 58               | 0.35        | SCC          | 165          | 18          | 0.045                  | 0.045                        | 0.045                           | 0.045                 | 0.045                | 0.045                  | 0.45        |
| 23  | 27 191                      | 58               | 0.35        | SCC          | 165          | 18          | 0.045                  | 0.045                        | 0.045                           | 0.045                 | 0.045                | 0.045                  | 0.45        |
| 24  | 28 192                      | 58               | 0.35        | SCC          | 165          | 18          | 0.045                  | 0.045                        | 0.045                           | 0.045                 | 0.045                | 0.045                  | 0.45        |
| 25  | 29 193                      | 58               | 0.35        | SCC          | 165          | 18          | 0.045                  | 0.045                        | 0.045                           | 0.045                 | 0.045                | 0.045                  | 0.45        |
| 26  | 30 194                      | 58               | 0.35        | SCC          | 165          | 18          | 0.045                  | 0.045                        | 0.045                           | 0.045                 | 0.045                | 0.045                  | 0.45        |
Figure 1. Figure of pulse velocity test device.

Figure 2. Signal curve of longitudinal wave forms (top) and velocity chart (bottom) in an RPC cube (S63 mix design). Test frequency is 54 KHz.

Figure 3. Signal curve of longitudinal wave forms (top) and velocity chart (bottom) in an RPC cube (S73 mix design). Test frequency is 54 KHz.
6. Conclusions

Consequently, MRPC it is recommended to use pulse velocity as an indicator for evaluation of compressive strength \( (R^2 = 0.9001) \).

There was also a very significant relationship between dynamic elastic modulus and compressive strength in RPC, MRPC \( (R^2 = 0.9021) \). The Results of tests in RPC, MRPC showed a more favorable relationship between
Figure 5. Relationship between pulse velocity and compressive strength RPC, MRPC.

Figure 6. Relationship between compressive strength and dynamic modulus of elasticity RPC, MRPC.

Figure 7. The comparison of static and dynamic elastic modulus of concrete mixes for all formulas.

Table 5. Obtained models for RPC, MRPC.

| Model no. Obtained models | R² Parameters |
|---------------------------|---------------|
| 1 CS = 13.742(PV)² - 79.024PV + 183.1 R² = 0.9001 |     |
| 2 Ed = 0.0016(CS)² - 0.1521(CS) + 45.87 R² = 0.9021 |     |

1 CS: compressive strength (MPa), PV: pulse velocity (Km/s)
2 Ed: dynamic modulus of elasticity, CS: compressive strength (MPa)
compressive strength and dynamic modulus of elasticity than ordinary concrete.

The five formulas suggested by the researchers to obtain the modulus of elasticity yielded close and reasonable results. Meanwhile, the dynamic modulus of elasticity (Ed) increased on average by 19% over the modulus of elasticity (Ec). Due to the lack of any proposed relationship between dynamic elastic modulus and compressive strength and pulse velocity in the past, therefore two new proposed formulas for MRPC were proposed.

The benefits and results of the MRPC mix design are similar, compared to RPC. From a practical point of view, the ease of using MRPC is incomparable and very desirable.

The average modulus of dynamic elasticity of RPC, MRPC was 61% higher than that of SCC and 47% higher than that of conventional concrete (C).

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List of notations

V is the pulse transfer velocity (km/s)
L is the length of the path (km)
T is the duration of the pulse transfer (s)
f'c is the compressive strength (MPa)
\( \mu \) is the Poisson’s ratio
\( \rho \) is the unit weight (kg/m³)
Ec is the modulus of elasticity (MPa)
Ed is the dynamic modulus of elasticity (MPa)
k₁ is the correction factor for coarse aggregates
k₂ is the correction factor for mineral admixtures

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