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Effects of Coating Aggregates on Dynamic Properties of Concrete by Impact Resonance Method

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Abstract

Concrete structures may be subjected to dynamic loadings like earthquakes, impact, and vehicular loads. These loads may cause considerable damage to infrastructures and shorten their life span. To reduce the effects, improving concrete's dynamic properties is important. This can be done using granular elastic components and fibers in the production of concrete. This research explores the influence of using coated aggregates on the physical, mechanical, and dynamic properties of concrete. Experimental investigation on concrete with epoxy, epoxy-sand, and epoxy-crumb rubber as a partial replacement of coarse aggregates at different volume fractions ranging from 5% to 20% was conducted. Furthermore, the dynamic modulus of elasticity of concrete with coated aggregate was determined by measuring the resonant frequencies of flexural vibrations in a prismatic beam using an impactor (hammer). Results indicate that partial replacement of epoxy-crumb rubber coated aggregates in concrete shows a reduction in mechanical proprieties. However, significant improvements in the mechanical and dynamic properties of concrete were observed by the partial replacement of coarse aggregates with epoxy and epoxy-sand coated aggregates. Compressive strength and dynamic elastic modulus were enhanced by 12% and 10%, respectively, when concrete with 15% epoxy-sand coated was used. The results showed that concrete specimens using epoxy and epoxy-sand coated as a partial replacement for coarse aggregate have higher mechanical properties as compared to those of concrete specimens with epoxy-crumb rubber-coated aggregates. Moreover, the results showed that the calculated values of the dynamic modulus using the empirical relations proposed by Popovics and Hansen were overestimated as compared to the experimental values.

Keywords: epoxy-sand coated, epoxy-crumb rubber coated, resonant frequencies, flexural vibrations, dynamic modulus

1. Introduction

As concrete is one of the most commonly used materials in the construction industry, it is critical to investigate its mechanical and dynamic properties. The vast application of concrete in the construction industry has led to increasing demand for improved performance against impact and dynamic loads. Several energy-absorbing materials were added to improve the ordinary concrete resistance to impact or dynamic loads and significant development has been achieved in this area [1]. Using coated aggregates is one of the recent interventions that may potentially affect; the interface bond between coarse aggregates and the matrix, the local dynamic response at the interfacial transition zone, moisture interaction between coarse aggregates and the matrix, etc. Coating of aggregates with different mixed solutions and their influence to the aggregate's properties and the properties of concrete was explored in this study.

An aggregate particle's shape can be expressed by three independent properties: form, angularity, and surface texture. The shape reflects variations in a particle's proportion and the angularity reflects variations at the corners. Surface texture describes the irregularity of the surface at a scale too small to affect the overall shape or angularity. The three properties can be distinguished based on their various particle size scales. These characteristics are distinct from one another, which means that any one of them may change significantly without having an effect on the other two [2]. Therefore, improving the surface texture of aggregate particle's has effects on properties of concrete. The improvements are utilized by means of coating aggregates with geopolymer [3], epoxy and polymers [4], palm oil clinker powder (POCP) [5], clay [6,7], plastics [8-13], silicon [14], hydrophobic polymers and styrene-butadiene rubber (SBR) [15], and other nanoparticles.

Geopolymer coating of lightweight aggregates (LWA) has been investigated by Shahedan, N. F., et al., [3] and it has been proven to enhance the properties of lightweight aggregate. The coating of aggregate can decrease the water absorption, excellent durability and bonding strength. Geopolymer coatings are sustainable materials because of their low pollution, and environmental friendliness, as well as their superior performance. Lim, Taekyung, et al., [4] observed high-strength functional lightweight aggregates using epoxy-TiO_2 coating. They also indicated the strength properties of the LWA are dependent on the concentration of epoxy and coating method. Abutaha, F., et. al, [5], investigated the mechanical properties of palm oil clinker (POC) concrete using palm oil clinker powder to fill up and coat the surface voids of POC coarse aggregate under different (0-100%) replacement of coarse aggregates. By providing enough paste to coat the POC surface voids, POCP coating greatly improved the compressive strength of the POC concrete [5].

Clay-coated coarse aggregates were observed to cause higher values of drying shrinkage in concrete and adding extra water did not result in significant increases in its shrinkage property at later ages [6]. Moreover, a study conducted by [7] identified the effects of clay coating on concrete properties. The researchers selected four clay types: sodium montmorillonite (NaM), calcium montmorillonite (CaM), kaolin and illite to coat the coarse aggregate. Based on their findings, the compressive strength of clay-coated aggregates with NaM and CaM clays was significantly lower than that of the control mix by approximately 88% and 75%, respectively. Additionally, these two clay coatings also reduced the split tensile strength by 80% and 65%, respectively. However, kaolin and illite coatings essentially have no effect on compressive strength of concrete.

Plastic wastes such as Polyethylene (PE), Polypropylene (PP) and Polystyrene (PS) by mixing with various types of hot bitumen were also used for coating coarse aggregates in concrete [8-13]. Generally, these types of coating are described as Plastics Coated Aggregate (PCA).

PCA at a higher percentage (up to 25%) were found to improve adhesion property and aggregate strength [8]. Experimental investigation, on partially replaced coarse aggregates with coated aggregates with polypropylene waste plastic resulted in reductions in crushing strength (by 5.09%), impact strength (by 1.67%) and abrasion resistance (by 8.27%) as compared to uncoated coarse aggregates [9]. A separate study on PCA was observed to enhance binding capacity, Marshall stability, strength, and load bearing capacity for road construction application. In addition, the abrasion resistance and impact strength were improved when PCA was used [10-12]. Interestingly, their technology not only strengthened road construction, but also increased road life with reduced environmental impact.

According to Dawale, S. A. [13], plastic wastes (e.g., discarded carry bags, films, and cups) were used to coat coarse aggregates with bitumen. From the study, results indicated that there were improvements in properties such as water absorption, stripping value, and soundness. The PCA mixture has a lower penetration value and a higher softening point, as well as adequate ductility.

The study conducted by [14] investigated the effect of silicon coated aggregates on concrete properties. In the study, mechanical properties of concrete were investigated under different loading rates. Results revealed that, the compressive strength with silicon coated aggregates with 5% replacement level had slightly increased. However, for 10% and 15% silicon coatings, the compressive strength was reduced in all loading rates. In addition, a higher reduction in static modulus of elasticity (30% - 43.5%) was exhibited.

Furthermore, the study [15] investigated the effect of coating of scoria and Leca aggregates using hydrophobic polymers-polyvinyl acetate (PVA) and styrene-butadiene rubber (SBR) polymers on the mechanical and microstructural properties of lightweight concrete. Coatings were applied in single and double layers. Test results showed that, the compressive strength of mixtures containing scoria lightweight (coated with one or two layers) increased by 21%. Moreover, the compressive strength for mixes containing Leca lightweight aggregates increased by 13.5%.

The focus of the previous researches discussed above is mainly on non-dynamic properties of concrete with coated aggregates. In this study, the effect of coating aggregates with epoxy, epoxy-sand and epoxy- crumb rubber on the mechanical as well as the dynamic properties of concrete were experimentally investigated. The dynamic modulus of elasticity as determined by the impact resonance method is compared with the theoretical results obtained from the static modulus using the relation proposed by Popovics [16]. Moreover, the dynamic modulus is compared with the results determined from the compressive strength using the relationship developed by Hansen [17].

2. Materials, Mix Design, and Experimental Program

2.1. Material Characterization

For the preparation of concrete mixtures, Portland OPC 42.5 grade cement, sand and crushed stone with a maximum size of 25 mm were used. In this study, to coat aggregates, Sika -161 and T 19 - 32/1000 epoxy resins were used. Furthermore, crumb rubber particle sizes ranging from 2.5-3.5 mm and standard sand particle sizes ranging from 0.75-2.0 mm are used for coating aggregates. Table 1 shows the physical properties of standard sand, crumb rubber, sand and coarse aggregates. The gradation requirements of sand and coarse aggregates were checked and both aggregates satisfy the requirement set on ASTM C 136 [18]. Properties of epoxy resin (Sika - 161 and Epilox T 19-32/1000) and Polymeric coupling agent (BYK-C 8001) are presented in Table 2.

Table 1. Physical properties of standard sand, sand, coarse aggregates and rubber

Physical properties	Standard sand	Sand	Coarse aggregate	Crumb rubber
Specific gravity	2.6	2.5	2.7	1.03
Moisture content %	< 0.2	2.4	1.3	
Water absorption %	0.7	2.04	1.02	
Unit weight kg/m³	1580	1405	1615	720

Concrete specimens of various sizes were cast and tested. Tests were carried out in accordance with EN (European Norm) and ASTM (American Society for Testing and Materials) standards. Concrete mixtures with replacement of maximum 20% coarse aggregate by epoxy, epoxy - sand and epoxy- crumb rubber coated aggregates with an increment of 5% are considered.

Table 2. Properties of Epoxy resins and Coupling Agent

Sika -161 Epoxy [19]	Epilox® T 19-32/1000 [20]	Coupling Agent BYK-C 8001 [21]
density approx. 1.65 g/cm³ (23 °C) Shore D Hardness ~76 (7 days / +23 °C) (DIN 53 505) Compressive Strength > 45 N/mm² (mortar screed, 28 days / +23 °C / 50 % r.h.) (EN13892-2)	density approx. 1.14 g/cm³ (20 °C) liquid, solvent-free, crystallization-inhibited, low-molecular and low viscosity epoxy resin viscosity at 25 °C (1.0-1.3 (Pa·s))	density 1.035 g/cm³ (20 °C) melting point/range < -76 °F (< -60 °C) initial boiling point 194 °C (1,013 hPa) vapor pressure ca. 0.55 hPa (20 °C) Viscosity, dynamic 34 mPa.s (68 °F (20 °C))

The control mix is designated as CM-0, concrete with epoxy coated aggregates as ECA-n, with sand coated aggregates as SCA-n and with crumb rubber coated aggregates as RCA-n. The letter n indicates the replacement level (e.g., ECA-15 represents concrete with 15% replacement of coarse aggregate by epoxy-coated aggregates).

2.2. Mix Design

The proportion of materials is determined using a volume-based mix design method. Concrete mixtures incorporating coated aggregates with epoxy, epoxy-sand and epoxy-crumb rubber at 0%, 5%, 10%, 15% and 20% substitution of coarse aggregate were prepared. Cement, sand and coarse aggregate mix proportion of 1:1.5:3 was used, with a water-cement ratio for all mixtures was 0.45.

Manual coating is used for each of the coatings used in the study. For the epoxy coated aggregates, the aggregates are only coated with epoxy. For the epoxy-sand and epoxy-crumb rubber coated aggregates, initially the aggregates are coated with epoxy and are left for 45-60 min. The epoxy coated aggregates, and then thoroughly blended with the standard sand for the epoxy-sand coated aggregates and with crumb rubber for the epoxy-crumb rubber coated aggregates. During this process, the sand and crumb rubber stick on the surface of the epoxy coated aggregates (see Figs. 2b and 2c). Finally, the coated aggregates are allowed to dry for three days (under a temperature T = 20°C and relative humidity RH=70%) before being used to make concrete mixtures. It can be observed that the sand and crumb rubber particles are well distributed over the surface of the aggregates, see Figs. 2b and 2c.

Fig 1 shows samples of crumb rubber and standard sand used in this study for coating the natural coarse aggregates. Moreover, samples of coated aggregates with epoxy, epoxy-sand, and epoxy-crumb rubber are shown in Fig 2.

(a) crumb rubber (b) standard sand

Fig. 1. Crumb rubber and standard sand samples

(a) (b) (c)

Fig. 2. (a) epoxy coated (b) epoxy-sand coated (c) epoxy-crumb rubber coated aggregates

2.3. Experimental Program

2.3.1. Test Methods

Testing procedures for measuring the mechanical and dynamic properties of concrete, such as compressive strength, split tensile strength, static and dynamic moduli of elasticity of concrete are conducted in accordance with ASTM and EN test standards and tests are carried out on 28th days aged concrete specimens.

Compressive strength test (cube specimens with 150 mm dimensions) is conducted following EN 12390-4: 2019 testing procedure [22]. For split tensile strength test (cylindrical specimens with dimensions of 300 mm in length and 150 mm diameter), ASTM C496-96 [23] and EN 12390-6 [24] test procedures were performed. The static modulus of elasticity (cylindrical specimens with dimensions of 300 mm in length and 150 mm diameter) is determined as per EN 12390-13:2021[25] standard. Moreover, for dynamic modulus of elasticity test (beam specimen with 100mm×100mm×500mm), impact resonance testing was performed as per ASTM C215-08 standard [26].

2.3.2. Fundamental Transverse Resonant Frequencies

In the experimental program, using the Impact Resonance Testing (IRT), the fundamental transverse resonant frequency of concrete specimens was measured and the corresponding dynamic modulus of elasticity of concrete is calculated. For transverse vibration, the support nodes are located at a distance equal to 0.224 times the length of the specimen (L) away from the ends of the specimen. The schematic diagram of a test setup for a rectangular concrete prism with square dimensions of 100 mm and a length of 500 mm is shown in Fig. 3.

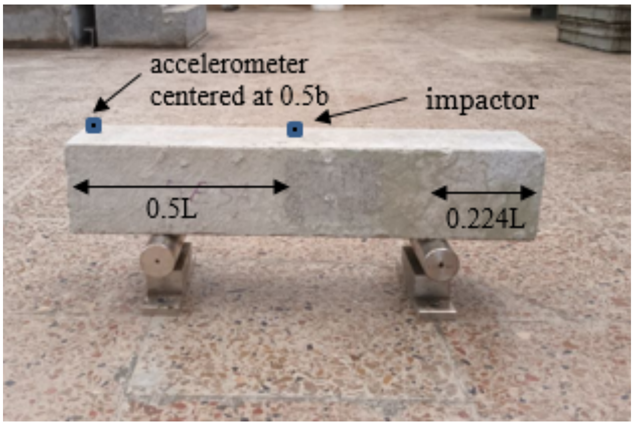


Fig. 3. Schematic of transverse mode (ASTM C215-08)

A hammer (small impactor of 750 gm), an accelerometer (Arduino type, MPU-6050) and a computer are used to test the impact resonance frequency. The impact point was at the mid span of the prism's top face, and the accelerometer was attached to the specimen's positioned 20 mm from the edge. The locations of the accelerometer, impact point, and boundary conditions remained consistent across all concrete specimens. To allow free vibration in the fundamental transverse mode with a free-free boundary condition, the supports are placed at nodal points. The instrumentation and experimental test setup employed in this study is shown in Fig. 4.

Fig. 4. Experimental Test set-up: accelerometer (Arduino type, MPU-6050) and impactor

2.3.3. Determination of Resonant Frequencies

Under free-free boundary conditions, a supported prismatic beam specimen is struck manually with an impact hammer to produce vibration. The Arduino UNO board was connected to a computer via Arduino software to record time domain signal of the specimen response received from the accelerometer and then transformed the recorded time domain signal into amplitude-frequency domain using MATLAB code based on Fast Fourier Transform (FFT). The resonant frequency (frequency corresponding to the peak amplitude) is then determined from the Frequency Response Function (FRF).

2.3.4. Dynamic Modulus of Elasticity

In this section, IRT method, which is a dynamic young's modulus measurement technique, is briefly described. According to ASTM C215-08, the dynamic modulus of elasticity of concrete, E_d, is calculated from the fundamental transverse frequency, mass, and dimensions of the test specimen. For the prismatic specimen, the dynamic modulus of elasticity (E_d) can be given by the following Eq. (1) [26]:

$$E_d = 0.9464 M n^2 T \left(\frac{L^3}{bt^3} \right) \tag{1}$$

where E_d is the dynamic modulus of elasticity (Pa), M is the mass of prism (kg), n is the fundamental transverse resonant frequency (Hz), L is the prism Length (m), b, t are the cross-sectional dimensions of the prism (m), and T is the correction factor.

The correction factor depends on the ratio of the radius of gyration, K, (for a prism $K = t/3.464$), the length of the specimen (L) and the Poisson's ratio. Numerical values of the correction factor for various values of Poisson's ratio and K/L are given in ASTM C215-08 [26].

3. Results and Discussions

The mechanical and dynamic properties of conventional concrete and concrete with coated aggregates (epoxy resin, epoxy-sand and epoxy-crumb rubber coated) were tested and results are presented in the following subsections.

3.1. Mechanical Properties

Test results on the compressive strength, split tensile strength, and static modulus of elasticity of concrete with various coating fractions are presented in Table 3 below. Three tests were conducted on each sample, and average values are presented. Additionally, graphs of the test results are shown in Figs. 5-7.

Table 3. Compressive, split tensile strength and static modulus of elasticity of concrete

Percentage replacement (%)	Compressive strength (MPa)			Split tensile strength (MPa)			Static Modulus (GPa)		
	Epoxy coated	Sand coated	rubber coated	Epoxy coated	Sand coated	rubber coated	Epoxy coated	Sand coated	rubber coated
0	37.79	37.79	37.79	2.37	2.37	2.37	29.98	29.98	29.98
5	38.77	40.81	37.42	2.43	2.38	2.24	30.68	31.16	29.54
10	37.28	41.03	36.64	2.25	2.49	2.16	27.70	29.68	28.05
15	34.59	42.41	34.97	2.28	2.43	2.12	27.25	28.59	27.40
20	33.46	41.17	34.11	2.16	2.30	2.08	28.22	29.73	25.64

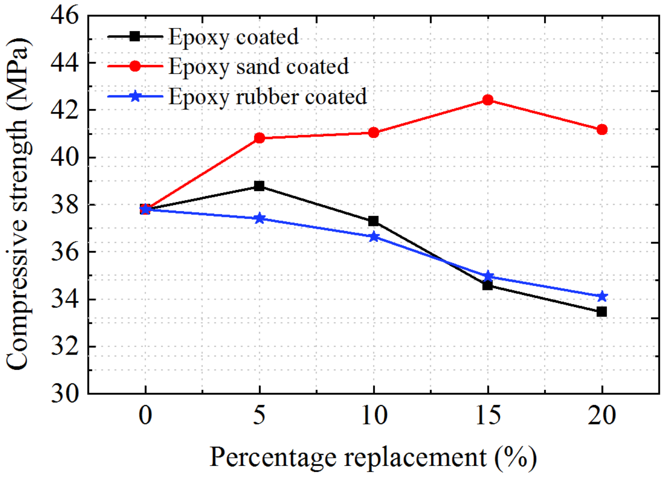


Fig. 5. Compressive strength (MPa)

Based on the test results shown in Table 3, the compressive strength of concrete with coated aggregates was in the range between 34.1 and 42.4 MPa. Optimal compressive strength of concrete was observed for SCA-15, which is an increment of 12%. The increment was observed due to the formation of rough texture of the surface when the aggregates were coated with epoxy-sand, which enhances the bond between the matrix and the aggregate surface. However, the maximum reduction in compressive strength was at ECA-20, i.e., approximately 11% lost with respect to the control mix. The strength reduction may be caused due to weak interface strength between the epoxy coated aggregates and the matrix.

For epoxy coated aggregates, a slight increment of 3% was noticed in its compressive strength at 5% replacement level. This is due to the presence of smaller, locally formed micro-cracks that changes the crack patterns at this localized area. According to a study in [27], the presence of primary micro-cracks did not affect the compressive strength of concrete, but remarkable reduction was observed as the crack width and crack angle increased. However, beyond 5% replacement level of epoxy-coated aggregates, a reduction in compressive strength ranging from 2% to 11% was observed. The reduction is caused by the development of smooth texture which decreases the contact area. This results a poor bond between the interface of aggregate and the matrix. For RCA-5, there is a slight reduction of 0.95% in compressive strength was achieved. For the other rubber coated aggregates, a reduction of 3% - 10% was observed.

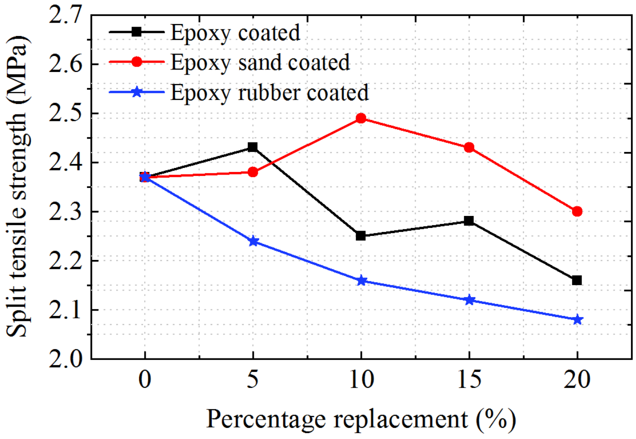


Fig. 6. Split tensile strength (MPa)

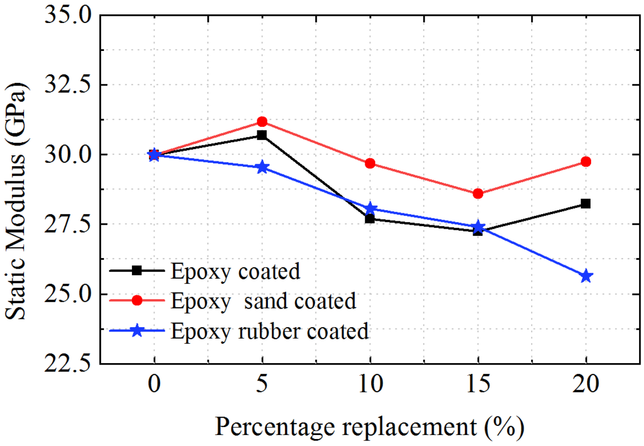
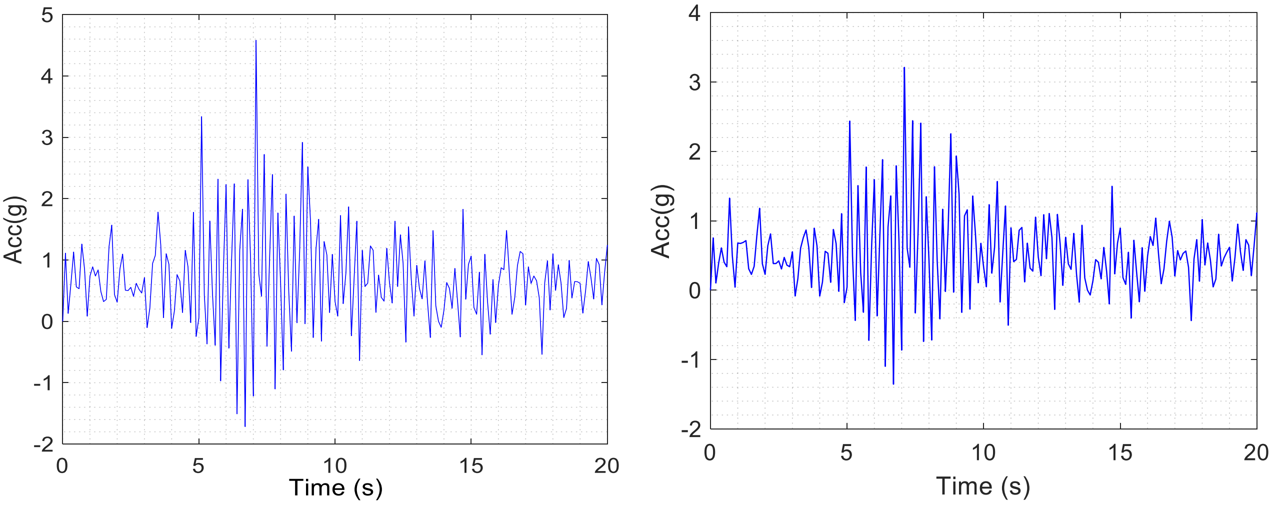


Fig. 7. Static Modulus of Elasticity (GPa)

As shown in Fig. 6, for split tensile strength, there is a higher reduction up to 12% was observed. Maximum split tensile strength is obtained when SCA-10 concrete mix was used, resulting an increment of 5%. Moreover, as shown in Fig. 7, better results in static modulus were achieved if ECA-5 and SCA-5 coatings have been used. It is also observed that, the optimal static modulus (4% increment) was achieved if SCA-5 mix was used. Unlike ordinary concrete, the increase in compressive strength is not directly associated with the increase of static modulus with partial replacement of epoxy-sand coated aggregates. It can be observed that the compressive strength of the SCA concrete increases with the replacement of coated aggregates, however the static modulus reduces with the increase in replacement of epoxy-sand coated aggregates.

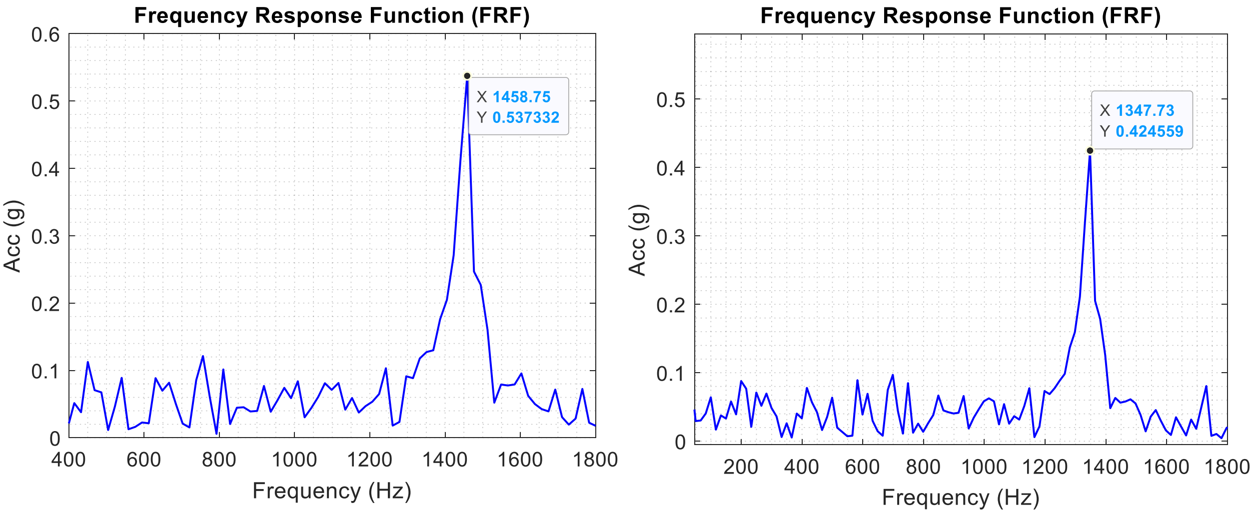
3.2. Dynamic Modulus of Elasticity (Impact Resonance Method)

The dynamic modulus of elasticity was determined by using the impact resonance method for concrete with coated aggregates of different coating materials. Samples of the acceleration time history is shown in Fig. 8 below. Moreover, Fig. 9 shows the Frequency Response Function (FRF) of SCA-5 and RCA-15 concrete specimens.



(a) SCA -5 (b) RCA -15

Fig. 8. Acceleration time history



(a) SCA -5 Test 2 (b) RCA -15 Test 3

Fig. 9. Samples of Frequency Response Function (FRF)

The dynamic modulus of elasticity of concrete, E_d, is computed using Eq. (1) and the results are presented in Table 4. For each concrete specimen, three repeated tests were performed and mean values of the resonant frequency were taken for the determination of the dynamic modulus of elasticity. For the tested specimen with a K/L ratio of 0.06 and a Poisson's ratio of 0.24, the correction factor (T) is 1.29 [26].

Table 4. Resonant Frequency and Dynamic Modulus of Elasticity

Notation	Mass of Prism (kg)	Average values		CoV (%)	Increment (%)
		Resonant Frequency (Hz)	Dynamic Modulus (GPa)		
CM-0	10.55	1452.30	33.96	3.47	-
ECA-5	10.72	1465.00	35.11	2.13	3.39
ECA -10	10.47	1423.31	32.37	1.99	-4.68
ECA -15	10.65	1385.43	31.20	1.17	-8.13
ECA -20	10.75	1365.63	30.59	3.93	-9.92
SCA -5	10.43	1457.04	33.79	2.60	-0.49
SCA -10	10.95	1448.19	35.05	3.04	3.21
SCA -15	10.98	1490.02	37.20	2.96	9.55
SCA -20	10.95	1411.98	33.32	1.53	-1.89
RCA-5	10.17	1499.16	34.88	1.37	2.72
RCA -10	10.59	1438.86	33.46	3.48	-1.47
RCA -15	10.95	1370.06	31.37	2.88	-7.63
RCA -20	10.86	1344.67	29.97	3.29	-11.75

As shown in Table 4, an optimal dynamic modulus of elasticity is obtained with SCA-15, which resulting nearly 10% increment compared to the control mix. While, for 5% replacement of aggregates with epoxy and epoxy-crumb rubber coated aggregates, there was an increment of 3.4 % and 2.7%, respectively. For RCA-20, a maximum reduction (approximately 12%) in dynamic modulus of elasticity is observed. In general, increasing the percentage level of coated aggregates with epoxy, epoxy-sand and epoxy-crumb rubber, reduction in the dynamic modulus of elasticity was exhibited. Moreover, concrete specimens with varying percentages of coated aggregate replacement, the CoV of the dynamic modulus of elasticity ranges from 1.17% to 3.93%.

3.3. Relationship between Compressive Strength, Static and Dynamic Moduli of Concrete

Many researchers have found relationships to correlate the static and dynamic moduli of elasticity. Based on a large sample of concrete specimens, with compressive strengths ranging from 24MPa to 161MPa, Popovics developed linear empirical relations that is given in the following Eq. (2) [16].

$$E_s = 0.83 E_d \tag{2}$$

where E_s is the static modulus of elasticity (GPa) and E_d is the dynamic modulus of concrete (GPa).

According to Hansen, an empirical relationship for concrete's dynamic modulus of elasticity and compressive strength is developed and given by the following expression [17].

$$E_d = 5.31 f_c^{0.5} + 5.83 \tag{3}$$

where E_d is the dynamic modulus of elasticity of concrete (GPa) and f_c is the compressive strength of concrete (MPa).

For comparison, the dynamic modulus of elasticity of concrete obtained from experimental tests (impact resonance method) and values estimated from the empirical relations using Eqs. 2 and 3 is presented in Table 5 below.

Table 5. Dynamic Modulus of Elasticity (Experimental and predicted values)

Notation	Compressive Strength (MPa)	Static Modulus (GPa)	Dynamic Modulus (GPa)			Ratio	
			Hansen (1)	Popovics (2)	IRT method (3)	(1)/(3)	(2)/(3)
CM-0	37.79	29.98	38.47	36.12	33.96	1.13	1.06
ECA-5	38.77	30.68	38.89	36.96	35.11	1.11	1.05
ECA -10	37.28	27.70	38.25	33.37	32.37	1.18	1.03
ECA -15	34.59	27.25	37.06	32.83	31.2	1.19	1.05
ECA -20	33.46	28.22	36.55	34.01	30.59	1.19	1.11
SCA-5	40.81	31.16	39.75	37.54	33.79	1.18	1.11
SCA -10	41.03	29.68	39.84	35.76	35.05	1.14	1.02
SCA -15	42.41	28.59	40.41	34.45	37.20	1.09	0.93
SCA -20	41.17	29.73	39.90	35.82	33.32	1.20	1.08
RCA -5	37.42	29.54	38.31	35.59	34.88	1.10	1.02
RCA -10	36.64	28.05	37.97	33.81	33.46	1.13	1.01
RCA -15	34.97	27.40	37.23	33.01	31.37	1.19	1.05
RCA -20	34.11	25.64	36.84	30.89	29.97	1.23	1.03

Moreover, Figs. 7 and 8 show the dynamic modulus of elasticity of concrete determined by the impact resonance testing method (experimental values) and the predicted values obtained from the formulas proposed by Popovics and Hansen, respectively.

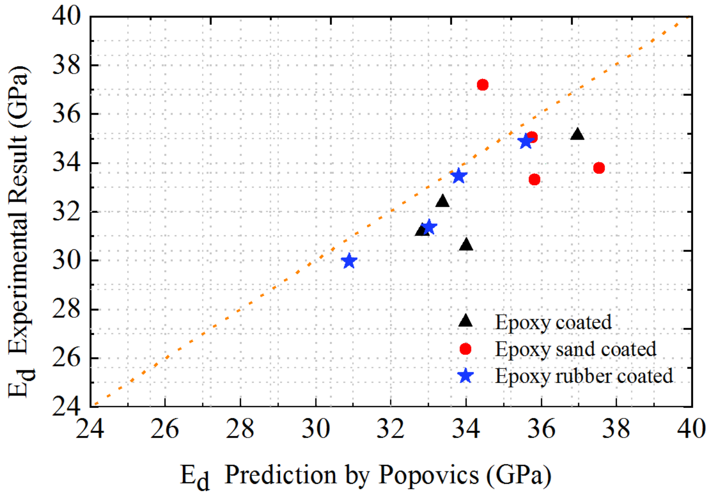


Fig. 7. Comparison of experimental and predicted values (by Popovics's formula) for the dynamic modulus of elasticity of concrete specimens

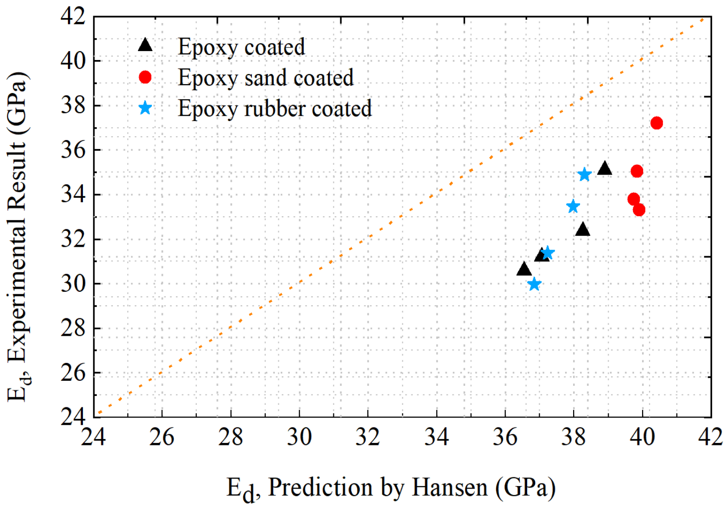


Fig. 8. Comparison of experimental and predicted values (by Hansen's formula) for the dynamic modulus of elasticity of concrete specimens

As shown in Table 5, the variation of the predicted dynamic modulus of elasticity of concrete calculated by Popovics's [16] formula to the corresponding experimental values ranges from 1.5% to 11%. Moreover, experimental measurements and the computed dynamic modulus of elasticity using Hansen's [17] formula differ by 8% to 23%. The findings showed that the dynamic modulus of elasticity obtained by measuring experimental values using the IRT method yielded a lower value than the predicted values by using the empirical relations proposed by both Popovics and Hansen. The variation is observed due to that, the relations (Eqs. 2 and 3) are developed for conventional concrete, whereas in this study the coarse aggregates were partially coated with epoxy, epoxy-sand and epoxy-crumb rubber. Thus, for concrete with coated aggregates, the suggested formula, in particular Hansen's formula, has significant differences and is not appropriate for predicting the dynamic modulus of elasticity of concrete.

4. Conclusions

The experimental processes of coating aggregates with epoxy, epoxy-sand and epoxy-crumb rubber were successfully carried out and has effects on the mechanical and dynamic properties of concrete. Based on the findings obtained from this study, coating aggregates with epoxy-sand can be used for concrete, which makes rough-textured aggregate surface and provide better interlocking and a good bond between the aggregate and the mortar mix.

Epoxy-sand coating of aggregates is found to enhance the compressive and splitting tensile strength of concrete up to a replacement of 15% of the natural coarse aggregates. Interestingly, the increase in compressive strength is not directly associated with the increase of static modulus for the concrete with partial replacement of epoxy-sand coated aggregates.

Generally, partial replacement of coarse aggregates with epoxy and epoxy-crumb rubber coated aggregates significantly reduces the mechanical properties of concrete. This reduction is due to the increase in crack width and the formation of smooth surface which weakened the interface bond strength between the coated aggregates and the matrix. However, partially replacing the coarse aggregates by epoxy and epoxy-crumb rubber coated aggregates can improve the dynamic properties of concrete.

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Notations

b, t	Cross-sectional dimensions of prism
E_d	Dynamic modulus of elasticity
E_s	Static modulus of elasticity
f_c	Compressive strength of concrete
L	Prism length
M	Mass of prism
n	Fundamental transverse resonant frequency
T	Correction factor

Abbreviations

ASTM	American Society for Testing and Materials
CoV	Coefficient of variation
EN	European Norm
FFT	Fast Fourier Transform
FRF	Frequency Response Function
IRT	Impact Resonance Testing
LWA	Lightweight Aggregates
PCA	Plastics Coated Aggregate
PE	Polyethylene
POC	Palm Oil Clinker
POCP	Palm Oil Clinker Powder
PP	Polypropylene
PS	Polystyrene
PVA	Polyvinyl acetate
SBR	Styrene-Butadiene Rubber

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