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The effect of grain size in rock-like materials on the strength and cracking process under uniaxial compressive stress

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ABSTRACT: Considering the importance of using tunnels and caverns created in rock masses under high stresses, it is necessary to study the crack development which leads to failure. There are various methods to study the mechanism of crack development in rock and rock-like materials. In recent years, the use of compressional wave velocity due to its unique and non-destructive features has been considered. In this research, concrete samples used as rock-like material were made with different mix designs, which included a discontinuous aggregate gradation ranges of 1.18-2.38 mm, 2.38-4.75 mm, 4.75-9.5 mm, 9.5-12.5 mm and a continuous gradation range with the maximum aggregate size of 12.5 mm and by loading in four stress levels of 40%, 60%, 80% and 90% of the strength of the samples, the effect of loading, and the growth and development trend of the crack in samples using the compressional wave velocity have been studied. The results indicated that by loading the samples up to 40% of peak stress, due to the closure of small cracks in the samples and the increase in the density of the samples, the compressional wave velocity increased. By increasing the loads up to 90% of strength, the compressional wave velocity decreases by about 10%. Then, by conducting experiments on samples with different ranges of gradation, the effect of aggregate dimensions on the growth and development of the crack using the compressional velocity was analyzed. The results show that by increasing the grain size, due to the consistency of the water-to-cement ratio and the aggregate volume to the volume of cement mortar, the porosity of the samples with larger granis increased more than the smaller ones. This factor has led to a decrease in the uniaxial compressive strength and also an increase in the specific weight by increasing the grain size which indicates that the specific weight of the coarse aggregates is more than fine ones. This issue causes that the increasing of specific weight as a result of grain size increase negates the porosity and compressional wave velocity tends to increase.

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1.INTRODUCTION

Rock behavior under stresses and loads in different stages of loading from zero to the final strength is not the same and depending on how much load is applied, the mechanism of rock behavior is different. According to Martin & Chandler (1994), during the beginning of loading to a certain level of stress, first, small holes and cracks in the rock are closed, and in this region the stress curvature is concave upward. Carrying on loading, very small internal cracks are appeared in the sample and the stress-strain diagram is linear. When loading lasts for a while cracks form in the sample permanently, which is followed by the combination of the cracks. Finally, the sample yields and a surface of fracture occurs in the sample [1]. An ultrasonic pulse compressional wave is one of the most suitable methods to analyze the fracture trend of rock and rock-like samples under compressive stresses. This test is of great importance due to its non-destructive nature, as well as its low cost and time of testing [2]. Ramel (1970) has proposed a model to evaluate the concrete quality by examining the travel of waves from concrete samples made of lime aggregates with different qualities [3]. Saad et al. (2005) constructed concrete samples with different mix designs to study the effect of compressional wave velocity on parameters such as water to cement ratio, curing time and aggregate gradation. According to their results, the compressional wave velocity has a direct inverse with curing time of concrete and an inverse correlation with the ratio of water to cement and aggregate size [4]. Zhao et al. (2006) evaluated the experimental study of ultrasonic wave damping in parallel with fracture and provided a better perception of the expansion of waves during discontinuities [5]. Azhari et al. (2013) created artificial cracks in samples of two types of constructional materials in Morocco and then performed ultrasonic pulse velocity tests to evaluate the effect of parameters such as the number of cracks and the crack angle on the velocity of the compressional wave passing through these rocks. According to the results obtained, increasing the number of cracks in the rocks is followed by decreasing the compressional velocity and in the rock samples with a crack angle of 25, the

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lowest wave velocity and with horizontal cracks the highest compressional velocity occurs [6]. By conducting uniaxial compressive tests and ultrasonic and X-ray experiments on five types of low porosity carbonate rock, Martins et al. (2016) analyzed the compressive stress applied to the rock samples and its effect on the compressional wave velocity and X-ray transmissions. They reported, according to their studies, that the compressional velocity increases during compressive loading to a level of stress at which the unstable growth of crack begins. This increase in the compressional wave velocity in marble is between 15% to 30%, and in limestone is between 5% to 10% of the initial values of the V_p. It followed that, when the crack expanded unsteadily, the values of longitudinal wave velocity will decrease [7]. According to the above, the ultrasonic experiments carried out on rock and rock-like materials in accordance with various variables such as rock type, pre-cracking in rock and concrete including crack number and crack angle, mix designs including water to cement ratio, concrete age and aggregate gradation have been studied. In this research, the effect of compressive loading on the development of cracks in concrete samples with discontinuous gradation from fine grains to coarse grains, as well as continuous gradation, has been investigated and the method of crack expansion in different loading stages has been investigated.

2.EXPERIMENTAL STUDY

As mentioned above, in order to evaluate the effect of aggregate gradation and grain size in rock-like materials on the strength of the samples and how the cracks grow, using the compressional wave velocity passing through the samples under uniaxial compressive stress, concrete cylindrical samples with a ratio of height to diameter equal to 2 and with discontinuous aggregate gradation of 1.18-2.38 mm, 2.38-4.75 mm, 4.75-9.5 mm, 9.5-12.5 mm, and continuous gradation with the maximum aggregate size of 12.5 mm were conducted in the laboratory. Then they were evaluated by conducting uniaxial compressive tests and ultrasonic pulse velocity. The details are explained below.

2-1- Preparation of samples

Tehran Portland cement type II was used in the preparation of samples. The aggregates used in construction of the samples were washed gravel and sand. To adapt the results of discrete element method software to the experimental results, round aggregates have been used. To grade the aggregates,

Table 1. The standard and available aggregate gradation ranges [8]

Sieve Size	Percent Passing Through the Sieve		
	Maximum Aggregate Size: 12.5		
	The percentage of available aggregates	The maximum percentage referring to the standards	The minimum percentage referring to the standards
12.5	100	100	100
9.5	84	89	83
4.75	50	66	51
2.38	40	47	31
1.18	27	33	18
0.6	14	21	10
0.3	10	13	5

Table 2. The fineness Modulus of aggregates[8]

Fineness Modulus			
The maximum value of curves	Maximum Aggregate Size: 12.5		
	The value for available aggregates	The minimum value referring to the standards	The maximum value referring to the standards
The fineness modulus of aggregates	4.75	4.26	5.00

Table 3. Properties of mix designs

Mix design	gravel (kg)	sand (kg)	cement (kg)	water (kg)	lubricant (kg)	Constructed volume (lit)
maximum aggregate size of 12.5	6.66	26.53	4.73	2.72	0.033	20
1.18-2.38	0	14.6	6.34	3.66	0.025	15
2.38-4.57	10.32	0	4.56	2.55	0.0165	10
4.57-9.5	10.32	0	4.56	2.55	0.0165	10
9.5-12.5	10.32	0	4.56	2.55	0.0165	10

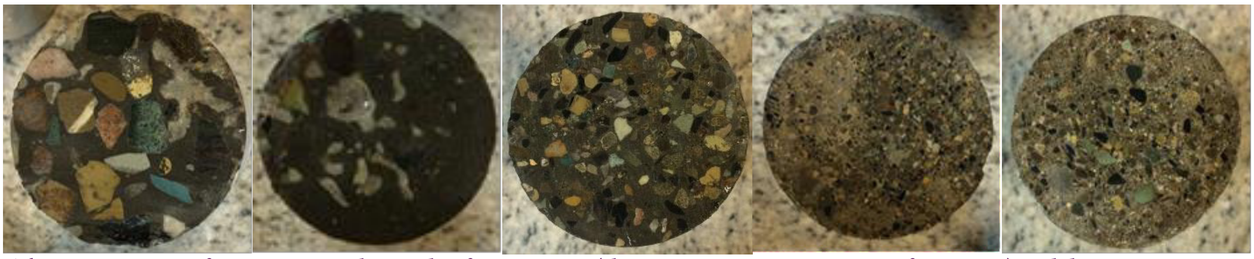

Fig. 1. The cross section of concrete samples made of continuous (the maximum aggregate size of 12.5 mm) and discontinuous aggregate gradation right to left: 1.1-12.5, 1.18-2.38, 2.38-4.75, 4.75-9.5, 9.5-12.5mm.

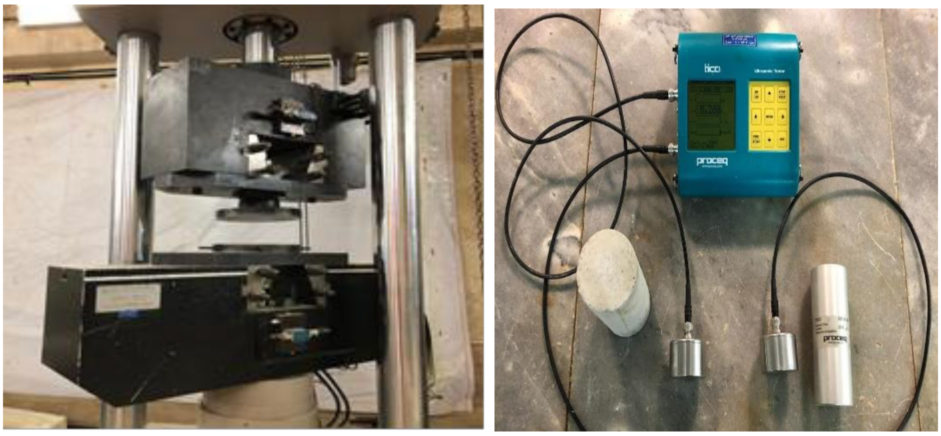

Fig. 2. Dartec-9600 Loading Test Device and Ultrasonic Pulse Velocity Tester

sieves number 4, 8 and 16 were used. The aggregate gradation and the characteristics of the mix designs of the samples are presented in Tables 1 to 3.

It is clear that in order to accurately compare the results of concrete samples, the water to cement ratio of the samples and the ratio of the amount of aggregate to the amount of cement consumption is considered constant. It should be noted that all steps of the mix design have been calculated based on the national concrete mix design of Iran [8]. In Fig. 1, the cross section of concrete samples made of continuous and discontinuous aggregate gradation is shown.

2-2- Sample examination

Initially, using a Dartec-9600 servo-controlled machine, 5 samples chosen from each aggregate gradation with loading rate and final displacement of the jaw 0.002 m/s and 30 mm respectively, according to the ASTM standard were examined and the average compressive strength of each design was obtained. In the second step, in order to evaluate the effect of grain size on the strength and the mode of crack development using the velocity of the compressional wave passing through the samples, for each aggregate gradation prior to loading in the specified stress levels, 5 samples were tested using the

Table 4. The average compressive strength of samples with various aggregate gradation

Sample gradation (mm)	continuous (D = 12.5)	1.18 – 2.38	2.38 – 4.75	4.75 – 9.5	9.5 – 12.5
Uniaxial compressive strength (MPa)	26.52	21.535	21.556	14.77	11.261

Table 5. The results of longitudinal wave velocity test for different aggregate gradation

Aggregate gradation	Sample number	The average velocity per (m/s) sample	The average velocity per (m/s) gradation
Gradation with the maximum aggregate size of 12.5 mm	c1	2357.5	2377
	c2	2447.5	
	c3	2390	
	c4	2302.5	
	c5	2387.5	
1.18-2.38	c1	1902.5	1922.5
	c2	1905	
	c3	1942.5	
	c4	1917.5	
	c5	1945	
2.38-4.75	c1	2445	2443.5
	c2	2487.5	
	c3	2392.5	
	c4	2407.5	
	c5	2485	
4.75-9.5	c1	2695	2636
	c2	2625	
	c3	2582.5	
	c4	2637.5	
	c5	2640	
9.5-12.5	c1	2752/5	2662
	c2	2595	
	c3	2527.5	
	c4	2720	
	c5	2715	

device TICO from PROTEQ brand. According to previous studies, the use of ultrasonic wave lengths in the range of 40-80 KHz is appropriate to evaluate concrete [4]. In the last step, in order to evaluate the effect of compressive loading in concrete specimens with different aggregate gradations on the velocity of compressional wave transmitted, 4 samples chosen from each gradation were loaded to 40%, 60%, 80%, and 90% of their peak stress (obtained from previous step) and were examined using ultrasonic pulse velocity tester.

According to Table 4, the compressive strengths of samples with various aggregate gradation are obtained.

In the next step, the compressional wave velocity test was performed on samples with different aggregate gradations and as shown in Table 5, the average velocity for each gradation is derived.

In the next step, for each specified level of stress, 4 samples chosen from each gradation were loaded by the servo-control device to 40%, 60%, 80%, and 90% of their peak stress

Table 6. The results of compressional wave velocity in 5 levels of loading during uniaxial compressive test

Aggregate gradation	Loading to the peak stress ratio	Longitudinal wave velocity (m/s)				The average velocity in each (m/s) loading
continuous gradation with the maximum aggregate size of 12.5 mm	0%	2377				2377
	40%	2380	2390	2390	2370	2382.5
	60%	2220	2200	2190	2150	2190
	80%	2080	2100	2110	2090	2095
	90%	2090	2080	2070	2090	2082.5
1.18 – 2.38	0%	1922.5				1922.5
	40%	1940	1940	1940	1930	1937.5
	60%	1850	1840	1840	1820	1837.5
	80%	1790	1780	1760	1750	1770
	90%	1760	1760	1750	1740	1752.5
2.38 – 4.75	0%	2443.5				2443.5
	40%	2450	2440	2440	2420	2437.5
	60%	2420	2440	2410	2400	2417.5
	80%	2380	2360	2310	2270	2330
	90%	2280	2270	2230	2140	2230
4.75 – 9.5	0%	2636				2636
	40%	2470	2430	2430	2410	2642.5
	60%	2500	2480	2500	2440	2570
	80%	2600	2580	2580	2530	2572.5
	90%	2380	2370	2350	2360	2365
9.5 – 12.5	0%	2662				2662
	40%	2670	2670	2670	2660	2667.5
	60%	2570	2560	2530	2540	2550
	80%	2410	2390	2410	2400	2402.5
	90%	2460	2480	2380	2390	2427.5

(obtained from previous step). It is obvious that for each level of stress new samples were used.

3- ANALYSIS OF LABORATORY RESULTS

In this section, according to the results of laboratory tests, the diagrams showing the effect of size on strength and crack growth in different loading stages have been provided by obtaining the velocity of the compressional wave passing through cylindrical concrete samples with different ranges of aggregate gradation. Then, by analyzing the trend of uniaxial compressive strength and compressional velocity variations with the change in the grain size of concrete samples, factors affecting the changes of these two parameters were investigated.

3-1- The effect of grain sizes in concrete samples on the uniaxial compressive strength

According to Fig. 3, the results of uniaxial compressive test show that increasing grain size is followed by uniaxial compressive strength decreases. It should be noted that all samples with discontinues gradation have the same mix design and the difference in their strength parameters indicates the effect of grain size and porosity of the samples.

One of the effective factors in reducing compressive strength is the increase of pores and porosity in concrete samples by increasing the size of aggregates. By observing the apparent surface of the samples, it is concluded that there are many pores in the samples with gradation range of 9.5-12.5 mm, in comparison with the samples with gradation range of 2.18-1.88 mm. Another observation is the presence of small cracks at the surface of concrete samples with the largest gradation range of 9.5-12.5 mm. The main reason for the presence of these small cracks at the surface of concrete samples is the phenomenon of shrinkage of cement mortar. This phenomenon is not observed in concrete specimens

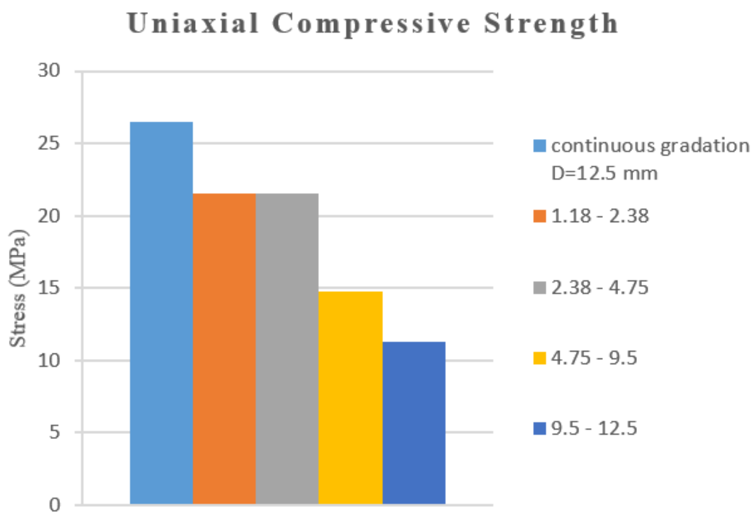

Fig. 3. Comparison of compressive strengths of different gradation ranges

Table 7. The comparison of results obtained from the uniaxial compressive tests of concrete with different aggregate gradations

D (mm)	UCS (MPa)	UCS [9] (MPa)	The percentage difference
7.6	15.150	20.956	27.703
8	14.659	19.835	26.091
8.4	14.168	18.714	24.285
8.8	13.677	17.592	22.250
9.2	13.187	16.471	19.937
9.6	12.696	15.349	17.286
10	12.205	14.228	14.218
10.4	11.714	13.106	10.624
10.8	11.223	11.985	6.358
11.2	10.772	10.862	1.212
11.8	10.241	9.742	-5.119

with finer gradation due to the presence of fine aggregates in concrete, which reduces the shrinkage of cement mortar more than the samples without fine aggregates.

The decreasing trend of compressional wave velocity in discontinuous aggregate gradation is similar to the findings of Shomali et al. in 2016[9]. Thus the correlations between the uniaxial compressive strength and the dimension of grades are as follows.

$$UCS = -1.2274D + 24.479 \quad R^2 = 0.953 \qquad (1)$$

$$UCS = -2.8035D + 42.263 \quad (R^2 = 0.8889) \qquad (2)$$

where UCS is the uniaxial compressive strength and D is the dimensions of grades whose units are MPa and mm, respectively.

According to the table above, by increasing the aggregate dimensions, the percentage difference between the correlations decreases. Also, this percentage difference may be due to the difference in mix designs and water to cement ratio (The water to cement ratio in this study and in the study of Shomali et al. is equal to 0.575 and 0.3, respectively).

3-2- The impact of gradation on compressional velocity

By analyzing the output of longitudinal wave velocity test of samples with different gradations, it is concluded that by increasing the grain size, the longitudinal wave velocity increases. At first glance, this process is in contradiction to the decreasing trend of uniaxial compressive strength. In order to find the appropriate response, calculating the specific weight of concrete samples, the wave velocity increment due to the increase of the grain size is investigated.

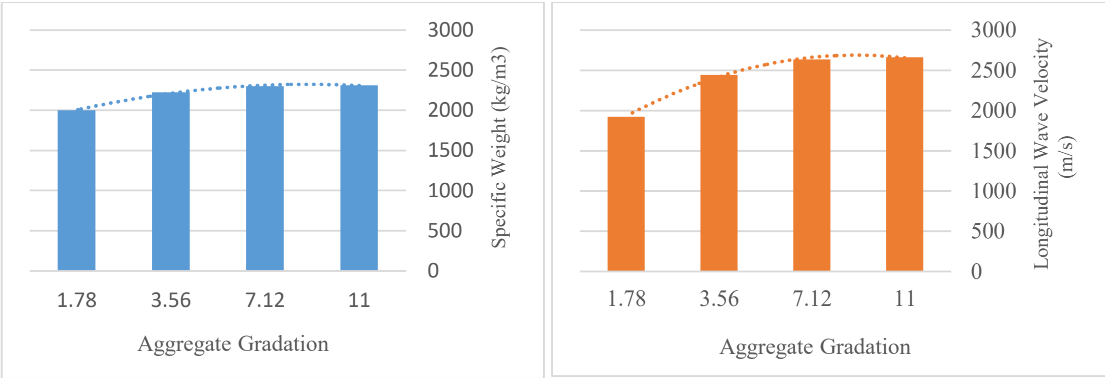

Fig. 4. Specific weight and velocity of the compressive wave passing through the samples in different aggregate gradation

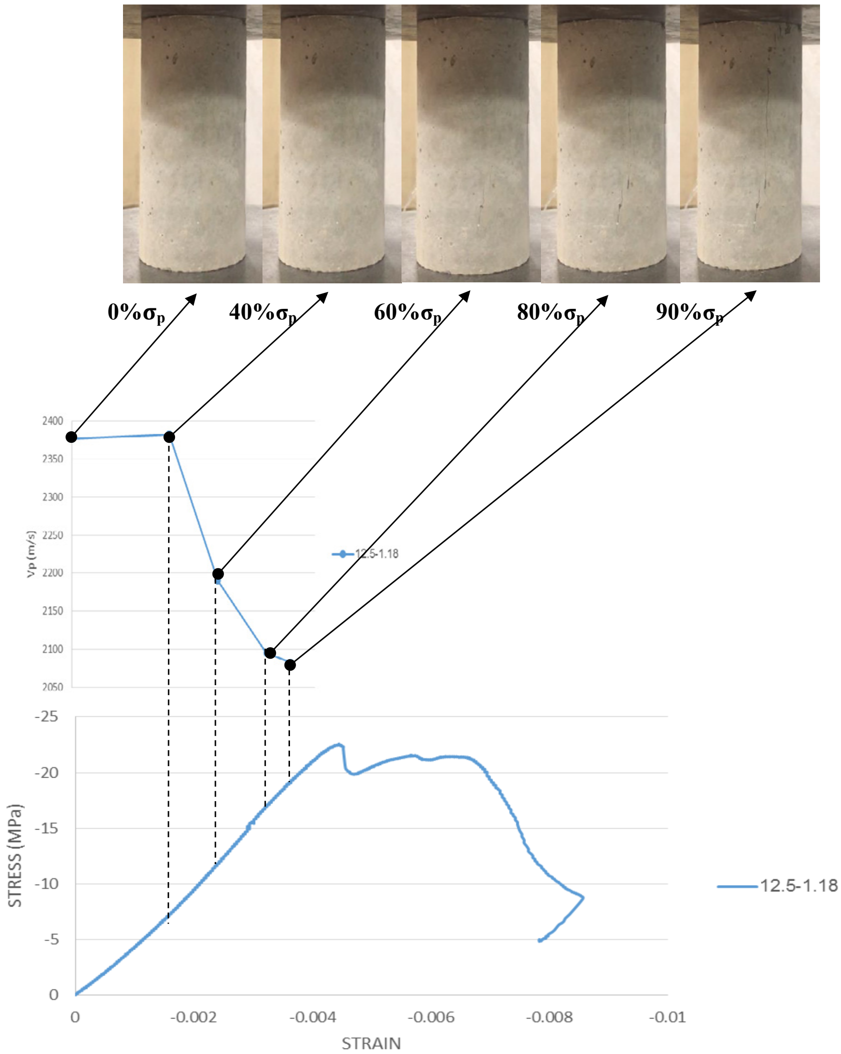

Fig. 5. The velocity of longitudinal wave under different loading conditions

According to the results, an increase in the size of aggregate and consistency of water to cement ratio and the ratio of aggregate to cement paste, leads to an increase in the velocity of the longitudinal wave length of the samples, due to the presence of larger aggregates which have greater density than the fine aggregates. This means that despite the increase in porosity of the samples, the impact of the aggregate size is greater than the porosity on the longitudinal wavelength.

As can be seen in Fig. 4, while aggregates with larger sizes exist in the samples, the compressional wave passes with further velocity through the coarse aggregates with larger density. Also the increasing trend of specified weight of the samples due to an increase in the velocity of compressional wave validates the results.

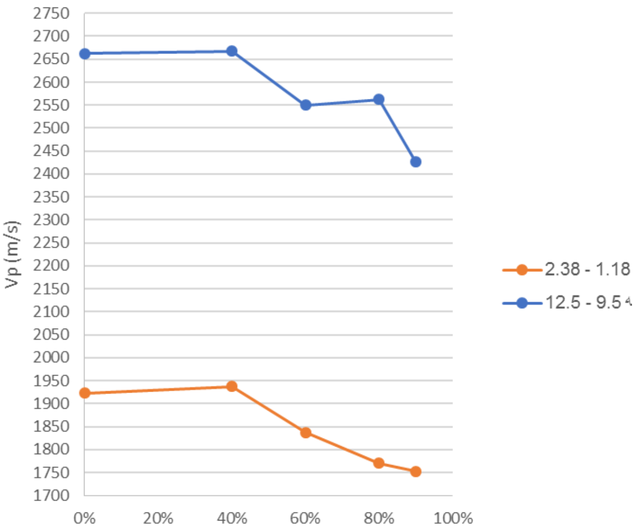

Fig. 6. The comparison of longitudinal wave velocity in fine and Coarse aggregates

3-3- The impact of stress level on crack development

The results of the wave velocity test of passing through the samples with different loading levels have been investigated. According to the results, the longitudinal wave velocity for some ranges of gradations is increasing to a certain stress level, and then, by further loading, the velocity of longitudinal wave confronts a sudden drop and a downward trend. This observation indicates that the compressive velocity is susceptible to the increase of micro-crack congregation in concrete samples. In other words, in the beginning of loading, the density of the mortar between the aggregates increases the compressive wave velocity. In Fig. 5, the stress-strain curve of the concrete sample with continuous aggregate gradation and the changes of compressional wave velocity passing through the sample for specific loading levels (40%, 60%, 80% and 90%) are shown. It was found that by loading the sample up to 40% of the final strength, by increasing the sample density resulting from the closure of the existing small cracks, the wave velocity increased and thus no changes can be seen in the appearance of the sample. With the onset of the process of decreasing the longitudinal wave velocity, during the imaging, cracks were observed in the surface, which developed by loading along the length of the sample and ultimately led to the failure of the sample under its final load.

In general, the variations in the velocity of the compressive wave parallel to the loading direction show a similar trend for all gradations. That is, the beginning of the loading, up to 40% of the final strength at which the cracks are closed and the mortar is compressed and as a result the compressive velocity increases. Then by increasing the stress level (more than 40% of the compressive strength) which leads to crack creation, growth and development, the compressional wave velocity decreases. This finding is similar to the results of studies by Martinez et al. [7]. By examining the graphs obtained from the compressional velocity under specified loading levels for different aggregate gradations, it is observed that the increase rate of the compressional wave velocity up to the stress level of 40% of the peak stress is greater in finer aggregate gradation than gradation with coarse aggregates. So that according to the Fig. 6, the wave velocity of the aggregate gradation range of 1.18-2.38 mm, up to 40% of its final strength, 0.7% increases and the aggregate gradation range of 9.5-12.5 mm, 0.2% increases. In the following, by increasing the compressive loading which leads to the formation and development of stable cracks in the sample, decreasing compressional velocity rate for both aggregate ranges of 1.8-1.38 mm and 5.9- 12 mm is equal to 8.8% of the compressional velocity before the loading of the samples.

4- CONCLUDING REMARKS

In the present study, the effect of aggregate size on crack propagation and strength changes in concrete samples was investigated by measuring the velocity compressional wave passing through the samples during compressive loading. For this purpose, uniaxial compressive tests and ultrasonic pulse velocity tests have been conducted. The results are as follows.

1. By increasing the gradation range in concrete samples varying from fine to coarse aggregates (with the maximum grain size of 12.5 mm), the uniaxial compressive strength obtained from the strain-control loading device is reduced.
2. The velocity of the compressional wave passing through the specimens increased by increasing the aggregate range, which is due to an increase in the specific weight of the aggregates used in the samples.
3. By applying compressive stresses to the concrete samples, the process of changes in the compressional velocity can be divided into two stages: in the first step, increasing loading up to 40% of the peak stress causes the velocity of the compressional wave passing through the samples for the whole aggregate gradation to increase. Continuing the loading, the compressional wave velocity significantly tends to reduce due to the creation of new cracks and their expansion.
4. By loading the concrete samples up to 40% of the peak stress, due to the aggregate interlock and the closure of small cracks in the samples, the increase of the compressional wave velocity is greater in finer aggregate gradation than gradation with coarse aggregates.

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