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Research Paper

THE CORRELATION BETWEEN AGGREGATE SHAPE AND COMPRESSIVE STRENGTH OF CONCRETE: DIGITAL IMAGE PROCESSING APPROACH

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The importance of the shape of aggregate particles on their mechanical behavior is well recognized. In concrete, the shape of aggregate particles has been related to durability, workability, shear resistance, tensile strength, stiffness, and fatigue behavior. In recent years, Digital Image Processing (DIP) techniques are widely used to analyze the particle shape characteristics of aggregate. In this study, the shape characteristics such as aspect ratio, elongation, flatness, form factor, roundness, shape factor, and sphericity were determined with digital image processing. Also, unit weight, slump, ultrasonic pulse velocity and compressive strength of concrete were determined. The test results indicated that there is a good correlation between the some shape properties of aggregate and compressive strength

Keywords: Aggregate shape, Digital image processing, Concrete, Compressive strength

INTRODUCTION

Since up to approximately 80% of the total volume of concrete consists of aggregate, aggregate characteristics significantly affect the performance of fresh and hardened concrete and have an impact on the cost of concrete (Hudson, 1999). The aggregates not only make concrete economical by occupying more volume, but also impart volume stability and increase durability. Also, the particle shape characteristics of the aggregate used can significantly affect the workability, strength, and durability of the concrete produced (Ozol, 1978; Kwan *et al.*, 1999; Erdogan, 2005; Erdogan *et al.*, 2006). The shape of aggregate particles can significantly influence certain properties of concrete, both in its fresh and hardened states (Jamkar and Rao, 2004). Also, the shape of aggregates used in concrete is an important parameter that helps determine many concrete properties, especially the rheology of fresh concrete and

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early-age mechanical properties (Erdogan, 2005; Erdogan *et al.*, 2006).

Aggregates shape, texture and grading have a significant effect on the performance of fresh concrete. Aggregate mixture with well-shaped, rounded, and smooth particles require less paste for a given slump than mix with flat, elongated, angular, and rough particles. At the same time, uniform grading with proper amounts of each size result in aggregate mixture with high packing and in concrete with low water demand. Optimized aggregate mixtures have high packing, requiring low amounts of paste. As a result, they are less expensive and will have less durability problems caused by the paste such as heat generation, porosity, and drying shrinkage (Quiroga and Fowler, 2004).

Shape and texture of coarse aggregates apparently are not as important as shape and texture of fine aggregate, but they play a role on the behavior of fresh and hardened concrete. Shape and texture affect the demand for sand. Flaky, elongated, angular, and rough particles have high voids and require more sand to fill voids and to provide workable concrete, thus increasing the demand for water (Shergold, 1953; Kaplan, 1958; Murdock, 1960). Poorly shaped aggregates may also increase segregation (Quiroga and Fowler, 2004). Flaky and elongated particles tend to produce harsh mixtures and affect finishability. According to Shilstone (1990), flaky and elongated particles, particularly those of intermediate sizes (between 3/8 in. (9.5 mm), and No. 8 (2.36 mm)), can affect the mobility of mixtures and contribute to harshness. Additionally, research shows that there is a clear relationship between shape, texture, and grading of aggregates and the voids content of aggregates (De Larrard, 1999; Dewar, 1999). In fact, flaky, elongated, angular, and unfavorably graded particles lead to higher voids content than, cubical, rounded, and, well-graded particles (Quiroga and Fowler, 2004).

Particle shape is important to the suitability of the aggregates with respect to their usage in several engineering materials. Elongated particles compared to cubic particles have a tendency to break along their long axis. Thus particle form affects the strength of the aggregates and life expectancy of the materials such as concrete, asphalt, and railroad aggregate. Spherical particles result in good rheological character in contrast to platy particles that determine the rheological character of concrete paste. Aggregates with a rough surface compared to a smooth surface will bind more securely in both asphalt and concrete (Fernlund, 2005a). As mentioned above, the importance of the shape of aggregate particles on the performance of fresh concrete is also well recognized. However, a little of studies are focused on the effect of aggregate shape to the hardened concrete properties.

The strength and the stiffness of coarse aggregate directly influence the behavior of hardened concrete. Although in normal concrete, strength is controlled by the paste or by the transition zone between paste and aggregate, the strength of high-performance concrete depends not only on the strength but on the mineralogy of coarse aggregate as well (Alexander, 1989; Cetin, 1998; Ezelding, 1991). Shape of the aggregates contributes to the strength value of concrete. Comparing the strength value between angular and smooth aggregates when slump is constant, there is no significant variation, as angular aggregates require more water than smooth aggregates. However, if w/c ratio and slump are kept constant with the use of admixture, there may be a reasonable increase in strength with the use angular aggregates.

Aggregate shape appears more and more as one of the key parameters characterizing the quality of aggregate, since it affects the properties of mixtures. When the proportion of flat particles in hydraulic concrete increases, the compression strength decreases, the cement consumption increases and the workability decreases (Frazao and Neto, 1984). Also, the British Standard (1984) allows no more than 35 to 40% of flat particles. Mehta and Monteiro (1993), state that flat and elongated particles should be limited to a maximum of 15% by weight of total aggregate. In general, it is preferable to have somewhat equidimensional rather than flat, thin, or elongated particles. The amount of flat and elongated particles in coarse aggregate samples can be determined following ASTM D 4791 (Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate), using a proportional caliper device. Manual measurements using a caliper device is a tiresome procedure that prohibits its use on a daily basis for quality control of aggregates on construction sites using concrete mixtures.

Alternative methods that permit rapid measurements of particle shape is also essential for good quality control of aggregates (Kuo *et al.*, 1996). Furthermore, particle shape measurements have to be done in a manual way that is not both cumbersome and time-consuming. Herein, Digital Image Processing techniques (DIP) are used to analyze the particle shape characteristics of aggregate (Mora *et al.*, 1998; Kwan *et al.*, 1999; Mora and Kwan, 2000; Kuo and Freeman, 2000; Masad *et al.*, 2001; Al-Rousan *et al.*, 2007).

In recent years, DIP techniques have been found widespread applications in many disciplines, including medicine, biology, geography, meteorology, manufacturing, and material science. Relatively, there have been a few applications of DIP in civil engineering. Several researchers had also investigated the role of aggregate shape in concrete mixture (Erdogan, 2005). Imaging technology has been used recently to quantify aggregate shape characteristics. Some studies have focused on characterizing the 3D shape of aggregates in concrete (Garboczi, 2002; Garboczi and Bullard, 2004; Fernlund, 2005a; Fernlund, 2005b; Erdogan *et al.*, 2006). Others have investigated the determination of shape properties of aggregate (Kwan *et al.*, 1999; Mora and Kwan, 2000) and grain size distribution (Fernlund, 1998; Mora *et al.,* 1998; Fernlund *et al.*, 2007). Also, others have been devoted to developing procedures to describe the shape of aggregates with an emphasis on elongation or form (Masad *et al.*, 1999; Barksdale *et al.*, 1991; Kuo *et al.*, 1996; Brzezicki and Kasperkiewicz, 1999; Weingart and Prowell, 1999; Maerz and Zhou, 1999; Rao and Tutumluer, 2000), angularity (Yudhbir and Abedinzadeh, 1991; Li *et al.*, 1993; Wilson and Klotz, 1996; Masad *et al.,* 2000; Kuo and Freeman, 2000), and texture (Hryciw and Raschke, 1996; Wang and Lai, 1998; Masad and Button, 2000). However, little research has been done in order to finding correlation between aggregate shape indexes and fresh and hardened concrete performance.

One major problem with the DIP technique is that only the two-dimensional projection of the particles is captured and measured. In other words, the third dimension (i.e., thickness) of the particles is not directly obtainable from the DIP results. Due to this problem, the DIP results have to be expressed in terms of area fractions rather than mass fractions (Yue and Morin, 1996). Consequently, they cannot be compared to those obtained by traditional methods and are more difficult to interpret. Also, there have been a few investigations on three-dimensional image analysis of aggregate (Kuo *et al.*, 1996; Rao and Tutumluer, 2000). In addition, the each of three dimensions of an aggregate is important and should be determined for image analysis studies.

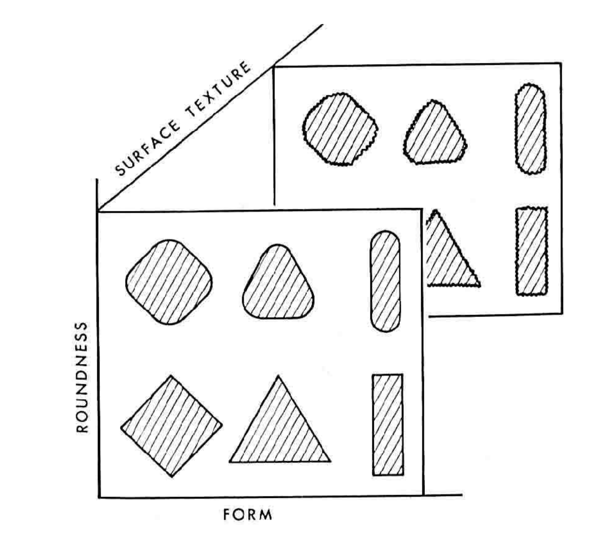
The present study was undertaken to investigate the effect of different type of coarse aggregate effect on the fresh and hardened Portland cement concrete behavior by a means of aggregate shape indexes such as aspect ratio, elongation, flatness, form factor, roundness, shape factor, and sphericity. The concrete produced with natural (uncrushed) river aggregate. Four different type of coarse aggregate was used. These aggregates were selected as flat, elongated, spherical and mixed shape. The shape properties were determined by digital image processing with two different views of aggregates. In this sense, the three dimensions of aggregate, the areas and perimeters of the views were determined. Test results were compared with previous studies and have been discussed.

AGGREGATE SHAPE PROPERTIES

Particle geometry can be fully expressed in terms of three independent properties: form, angularity (or roundness), and surface texture. Figure 1 shows a schematic diagram that illustrates the differences between these properties. Also, form, roundness and surface texture are essentially independent properties of shape because one can vary widely without necessarily affecting the other two properties (Barrett, 1980). Form, the first order property, reflects variations in the proportions of a particle. Angularity, the second order property, reflects variations at the corners, that is, variations superimposed on shape. Surface texture is used to describe the surface irregularity at a scale that is too small to affect the overall shape (Barrett, 1980; Masad, 2004)

Different researchers are using different shape indexes to describe the shape of aggregate particles and even different definitions for the same shape index. Barksdale *et al.* (1991) defined the flatness as the ratio of thickness to width and the elongation as the ratio of width to length while Kuo *et al*. (1996) defined the flatness as the ratio of width to thickness and the elongation as the ratio of length to width. They also used different definitions for the shape factor and sphericity. Besides, many researchers discussed the image analysis techniques used by most of the available imaging systems that utilize different mathematical procedures for the analysis of aggregate shape characteristics (Kuo and Freeman, 2000; Masad *et al.*, 2005; Al-Rousan *et al.*, 2007). These measurements have been explained in more detail below.

Figure 1: The Hierarchical View of Form, Roundness, and Surface Texture (Barrett, 1980)



In this study, for the first order of shape, form, the imaging index proposed is: shape factor, aspect ratio, sphericity, flatness, and elongation are measured for each aggregate particle. To properly characterize the form of an aggregate particle, information about three dimensions of the particle is necessary (longest dimension [L], intermediate dimension [I] and shortest dimension [S]). For the second order of shape, roundness, the imaging index proposed is: roundness is measured for each aggregate particle. It is also clear that form factor reflects changes in aggregate form, roundness, and surface texture (Kuo and Freeman, 2000).

Shape Factor: Shape factor is defined as

$$Shape \cdot Factor = \frac{S}{\sqrt{I.L}}$$

Kuo *et al.*, 1996; Masad *et al.*, 2001) ...(1)

Aspect Ratio: Aspect ratio is defined as

$$Aspect \cdot Ratio = \frac{L}{I}$$

(Kuo and Freeman, 2000) ... (2)

Sphericity: Sphericity is among a number of indices that have been proposed for measuring the form in terms of the three dimensions.

$$Sphericity = \sqrt[3]{\frac{I.S}{L^2}}$$

(Krumbein, 1941; Barrett, 1980; Kuo *et al.,* 1996; Masad *et al.*, 2001; Masad, 2004; Al-Rousan *et al.*, 2007)...(3)

Flatness: Flatness is defined as

$$Flatness = \frac{S}{I}$$ (Masad, 2004) ...(4)

Elongation: Elongation is defined as

$$Elongation = \frac{I}{L}$$

(Masad, 2004) ...(5)

Roundness: This is a shape factor that has a minimum value of 1 for a circle and larger values for shapes having a higher ratio of perimeter to area, longer or thinner shapes, or objects having rough edges. For the image analysis system used in this study, Roundness is defined as:

$$Roundness = \frac{P^2}{4.\Pi.A}$$

(Kuo *et al.*, 1996; Al-Rousan *et al.*, 2007) ...(6)

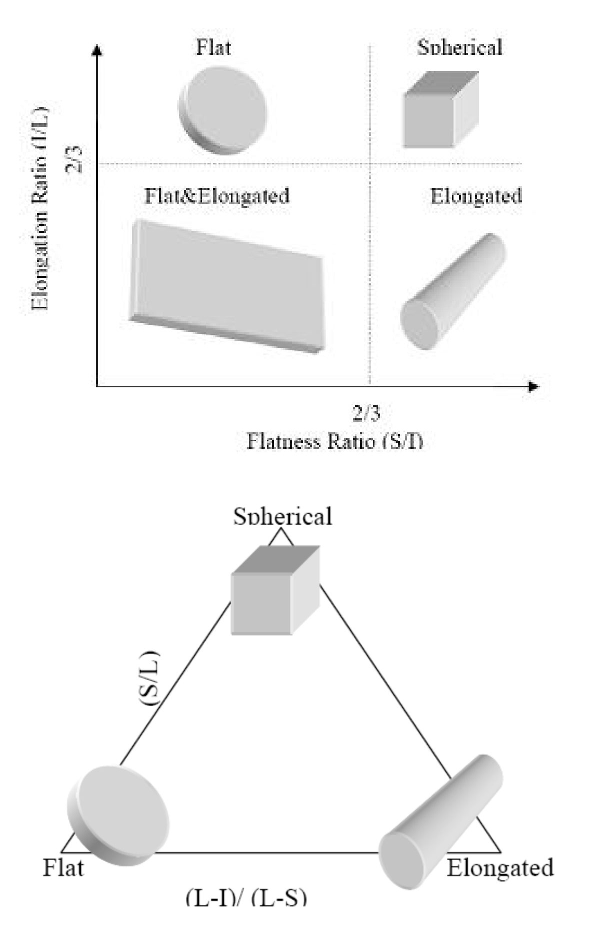
Form Factor: Several parameters based on object dimensions have been proposed in the literature to measure different aspects of aggregate shape. Form factor compares the perimeter of an equivalent circle to the perimeter of the particle. An equivalent circle has the same area as the particle. Because angularity and texture influence the perimeter of a particle, it follows that form factor not only is influenced by particle form but also reflects angularity and texture as well (Masad *et al.*, 2001). Form factor has been used to describe surface irregularity and is defined as:

$$Form \cdot Factor = \frac{4.\prod.A}{P^2}$$

(Kuo and Freeman, 2000;
Masad and Button, 2000;
Masad *et al*., 2001) ...(7)

Furthermore, quantification of form requires the measurement of the length, breadth and thickness of a particle. A number of different identifications have been used historically. Most previous authors have firstly identified the L dimension, defined as the maximum caliper dimension, and have then measured the I and S dimensions orthogonal to L (Blott and Pye, 2008). Zingg (1935) was indicated that the particles classified four base classes as mentioned in Figure 2a with using above measurement system. Also, Sneed and Folk (1958) consider Zingg's diagram to be inadequate in that it contained only four form classes which divided the field of form variation very unequally. They suggested that only three end-members limit the system of dimensional variation: a prolate spheroid with one long axis and two short ones (L > I = S), an oblate spheroid with two long axes and one short one (L = I > S), and a sphere with all axes equal (L = I = S). A number of different notations have been used historically to refer to these three classes, including, stengelig, flach and kugeligand (Zingg, 1935), rod, disk and cube (Krumbein, 1941), columnar, flat and spherical (Blott and Pye, 2008). Sneed and Folk (1958)'s three classes are also used in this study with different notation as elongated, flat, and spherical, respectively (Figure 2b).

Figure 2: a) Four different particle shapes (Zingg, 1935); b) Three different particle shapes (Sneed and Folk, 1958)



MATERIALS AND METHODS

In the study, ASTM Type I Portland cement (CEM I 42.5 R) a product of Limak Cement Plant, Ankara, Turkey and tap water were used for all mixtures throughout the study. Physical properties and chemical composition of

Portland cement are shown in Tables 1 and 2, respectively. The cement content was not varied as 500 kg/m^3 for a constant all specimens. Super plasticizer (SP)-Glenium 303 produced from BASF was used in tests. Properties of SP are shown in Table 3.

Table 1: Physical Properties of Portland Cement

CEM I 42.5 (Ordinary Portland Cement)	Results	TS EN 197/1 Standard data	
		(min)	(max)
2 days Compressive Strength, (N/mm^2)	27.9	20.0	-
7 days Compressive Strength, (N/ mm^2)	44.9		
28 days Compressive Strength, (N/mm^2)	55.9	42.5	62.5
Initial set time, (minute)	170	60	-
Final set time (minute)	230		
Volume expansion, (mm)	1	-	10
Specific surface, (cm^2/gr)	3285	-	-
Specific gravity	3.17		

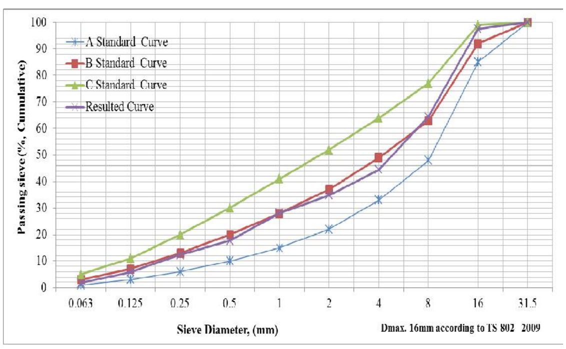
Table 2: Chemical Properties of Portland Cement

	Results	TS EN 197/1 Standard Data (max)
Heating loss (%)	2,03	5,00
Insoluble matter (%)	0,25	5,00
Cl_2 (%)	0,0102	0,10
SiO_2 (%)	20,54	-
Al_2O_3 (%)	5,12	-
Fe_2O_3 (%)	3,69	-
CaO (%)	62,98	-
MgO (%)	1,70	-
SO_3 (%)	2,88	-
Main constituent (%)		
C_3S	53,2	
C_2S	16,7	
C_3A	7,6	
C_4AF	10,7	

Table 3: Properties of Super Plasticizer*	
Material Structure	**Based Polycarboxylic Ether**
Color	Light green
Specific gravity (g/cm3)	1,023 - 1,063 kg/liter
The chlorine content % (EN 480-10)	< 0,1
Alkali content % (EN 480-12)	< 3
Note: * +20 ° C, relative humidity of 50% was obtained.	

Natural river aggregate was used as the aggregate material. The maximum size of coarse aggregate was 16 mm. The particle size distribution of aggregates in the study is 30% for 0-2 mm, 15% for 2-4 mm, 20% for 4-8 mm and 35% for 8-16 mm (Figure 3). The saturated surface dry specific weights of aggregates used in the study, 2.56 for 0-2 mm, 2.60 for 2-4 mm, 2.61 for 4-8 mm and 2.62 for 8-16 mm, respectively. In this study, first size fractions in coarse aggregate were selected by hand as flat, elongated, and spherical as mentioned below. In addition, a control mixture containing all of aggregate shapes was prepared. So, four different aggregate mixture types were selected by a means of shape properties. For the imaging process, four aggregate fractions were analyzed as flat, elongated, spherical, and mixed for 16 to 8 mm in this study. Designation codes of the aggregate fractions are given in Table 4. The concrete mix proportions are given in Table 5. The same water-to-cement ratio for the all mixtures was selected to be 0.30. Concrete mixtures have been made according to C 192/ C 192M – 02.

Figure 3: Grain-size Distribution Curve



For each mix, three specimens of 100 mm diameter and 200 mm height were prepared. After 1 day of moist curing, specimens from each mixture were cured in lime-saturated water at 23±1 °C until 28 days. The compressive strength tests were performed with ELE Autotest 3000 testing machine as defined in TS EN 12390-3. All the results are obtained 28 day specimens of each mix type and each result is from an average of three test specimens.

Compressive Strength Test

The compressive strength test was conducted according to ASTM C 39 "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens." In general, compressive strength was tested at ages of 28 days on three 10 cm × 20 cm cylinders. Before testing, the specimens were cured in a moisture room at 100% humidity.

Table 4: Designation Codes of the Aggregate Fractions

Mixture	Designations	
	Aggregate Type	Aggregate Shape
M1	Natural Aggregate(16 to 8 mm)	Flat
M2		Elongate
M3		Spherical
M4		Mixed (Control)

Table 5: The Mixture Proportions for 1 m³ Concrete

Materials	Flat Mixture (M1)	Elongated Mixture (M2)	Spherical Mixture (M3)	Control Mixture (M4)
Water/cement ratio	0.30	0.30	0.30	0.30
Cement (kg)	500	500	500	500
Water (kg)	150	150	150	150
SP agent (kg)	7,5	7,5	7,5	7,5
Natural aggregate (0-2), kg	529	529	529	529
Natural aggregate (2-4), kg	264	264	264	264
Natural aggregate (4-8), kg	352	352	352	352
Natural aggregate (8-16), kg	619	617	618	622

Imaging System

The DIP system used by the authors is a Nikon D80 Camera and Micro 105 mm objective manufactured by Nikon. Figure 4 shows the setup of the system. Two planes, perpendicular to each other, were covered with a scaled paper and fixed together to form the base and the background planes for the image acquisition setup. Whenever taking a picture, a white cotton cloth was placed on the background to obtain better contrast between the aggregate and the background pixels. The tests were performed in a dark room. Four fluorescent light sources have been positioned on the base plane to make the borders of the aggregates more visible for digital measurements. The flashlight of the camera was not utilized during image acquisition.

Figure 5 shows 3-D views of two regular-shaped solids, a rectangular box. Clearly, both the top and front views of the solid are identical rectangles. Using a 2-D image analysis setup consisting of only top camera and capturing an image of each solid would not be effective in distinguishing the 3-D shapes of the solids (Rao and Tutumluer, 2000). In this study two images from top and front views were obtained by imaging system for capturing the each

Figure 4: Schematic of the Image Analysis Systems (a) for top view (b) for front view

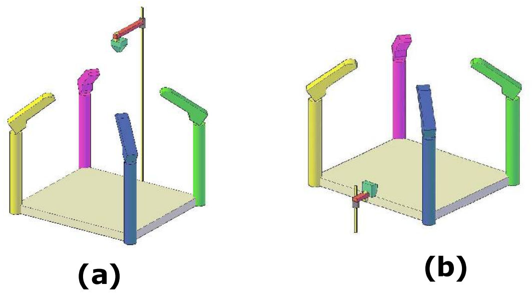
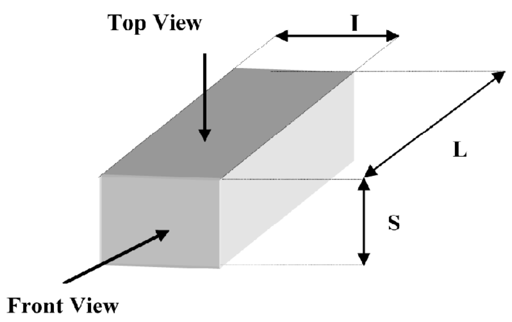


Figure 5: Three-Dimensional Views of Two Regular-shaped Solid: Rectangular Box



length of aggregate (i.e., small, intermediate, and long) as showed in Figure 6. One image was obtained from top view and the other image was front view.

Figure 6: Aggregates Top and Front Views

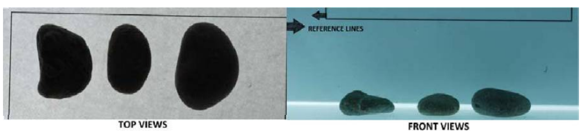
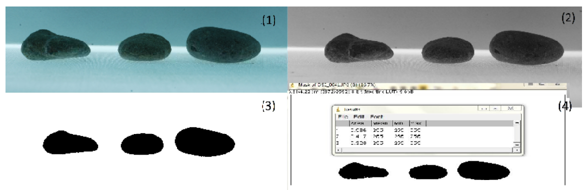


Image Processing

Digital-image processing consists of converting camera pictures into digital form and applying various mathematical procedures to extract relevant information from the picture. This section describes the image-analysis methods used to aggregate shape properties. The output of camera was a 3872-2592 pixel, 32-bit digital image of RGB color. The aggregate particles had to be identified prior to analysis. Image J was used as the image analysis program. Threshold gray intensity therefore had to be chosen. The gray intensity measured on a given point was compared to the threshold value. Then, the initial gray image was converted into a binary image in which the aggregate particles that have lower gray intensity than the threshold value were set to black while the background was set to white. Applying a global threshold value for all the image worked well only if the objects of interest (aggregate particles) had uniform interior gray level and rested upon a background of different, but uniform, gray level. This was made possible in this study by placing aggregate particles on white background. The original image (32-bit digital image of RGB) (1), 8-bit 256 gray scale image (2), 1-bit binary image (3) and output of Image J image analysis program (4) are shown in Figure 7.

Figure 7: Image Processing Steps



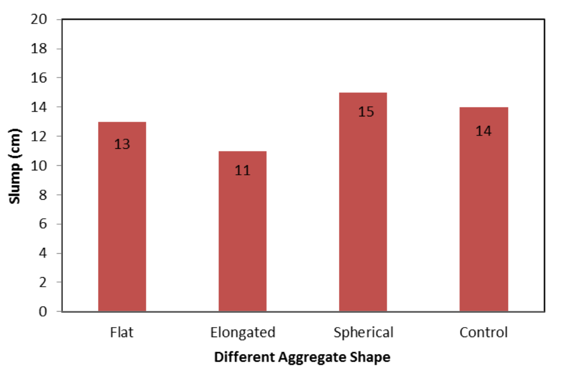
RESULTS AND DISCUSSION

In the following sections, the effect of aggregate shape on the behavior of concrete mix by compressive strength has been presented. Also, correlation between the aggregate shape properties and compressive strength of concrete has been presented. The findings of the experimental tests have been compared with other studies previous studies and discussed.

Fresh and Hardened Concrete Results

Compressive strength was conventionally evaluated the main properties of concrete. As a result from Figure 8 spherical aggregate mixture (M3) is the best mixture and flat aggregate mixture (M1) is the weakest mixture. Similarly, Neville (2010) indicated that flat particles produce lower compressive strength. These imply that blade (flat and elongated) and disk (flat) aggregates have low strength.

Figure 8: The Relationship Between Slump and Shape of Aggregates



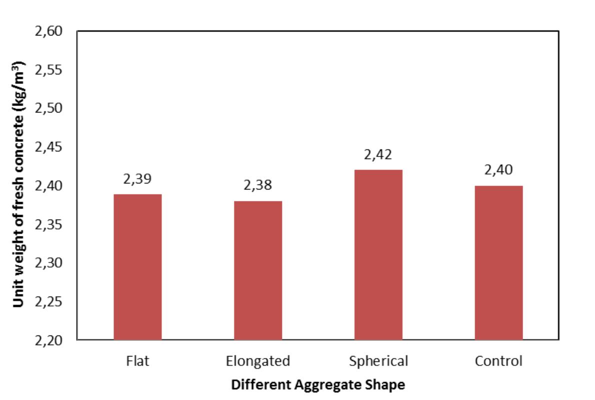
Aggregates having more angularity and rough surface texture the mechanical bond between the aggregate surface and cement paste, by virtue of interlocking, influences the strength of concrete (Kaplan, 1959). The shape and texture of crushed sand particles could lead to improvements in the strength of concrete due to better interlocking between particles. However, angular fine aggregate produces mortar of lower workability than spherical sands for the same water content, or the same volume of cement paste

Figure 8 shows that slump of concretes produced with spherical aggregates is more higher than slump of concretes produced with flat, elongated and mix type aggregates. By virtue of, the spherical aggregate surface area is less and because of less friction of spherical aggregates in concrete, workability is good than concretes produced with other aggregate types. Irregular shape and rougher texture of angular aggregate demand more water than spherical aggregated (Neville, 2010). The slump of concretes produced of mixture aggregates is more higher than the slump of concretes produced of flat and elongated aggregates because of that there were spherical aggregates in mixture. According to Shilstone (1990), particle shape has a major influence. Furthermore, mixes containing spherical and equi-dimensional particle sizes have better pumpability and finishability, and produce totally higher strengths and lower shrinkage than mixes containing flat and elongated particles.

Fresh concrete unit weight depends on voids in concrete, workability, aggregate grading and aggregate type. As a result from Figure 9 the concrete that has been made with elongated aggregate had the minimum unit weight equivalent with 2.38 and after that the increasing in unit weight has been observed orderly from flat aggregate, spherical and control aggregates that are 2.39, 2.40 and 2.41 orderly.

The effect of shape and texture of coarse aggregates on strength become significant in

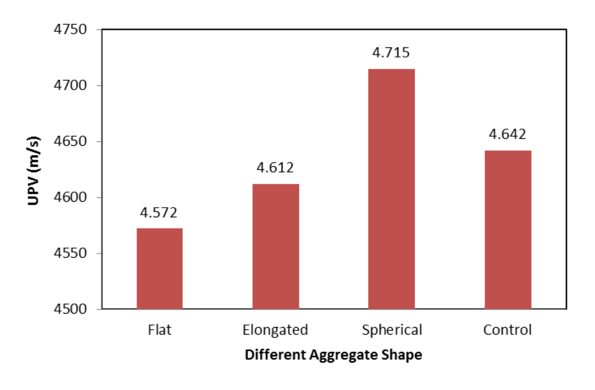
Figure 9: The Relationship Between Unit Weight Of Fresh Concrete and Shape Of Aggregates



the case of high strength concrete. In addition, shape and surface texture have more pronounced effect on flexural strength than compressive strength (Neville, 2003). Shilstone (1990) stated that well shaped aggregates are more desirable and produce consistent higher strengths than poorly shaped aggregates. The influence of shape and texture of coarse aggregate on the strength of concrete varies in magnitude and depends on the water-cement ratio of the mix.

The effect of shape and surface texture of aggregates on mechanical properties is often

Figure 10: The Relationship Between UPV and Shape of Aggregates



not a factor in conventional concretes (30-40 MPa), although these properties may cause an increase in the water demand. For these concretes, the hydrated cement paste and the transition zone around the aggregate are relatively weak. Consequently, the water/cement (w/c) ratio controls the mechanical properties of concrete for the same degree of hydration (Donza *et al.*, 2002). In previous studies, it was found that the uncrushed aggregates need lower water than crushed aggregates and uncrushed aggregates cater higher strength in concrete of medium grade. Again uncrushed aggregates are cheaper than crushed aggregates in the market of developing country such as Turkey. So from the study (Sharmin *et al.*, 2006), it can be concluded that uncrushed aggregates are appropriate for medium grade concrete for better performance in terms of strength and economy. Hence, in this study 40-50 MPa concrete mixtures and uncrushed aggregates were selected.

Particle Shape Analysis

Particle shape analysis was carried out in terms of some shape properties. The mean value and Standard Deviation (SD) for each shape properties of aggregates is listed in Table 6. The results showed that there exist distinct morphological characteristics for different particle shapes (i.e., flat, elongate, spherical, and mix).

Correlation Between Shape Characteristics and Compression Strength

In the following sections, the correlation between some shape properties of aggregate and compression strength of concrete are

Table 6: The average values of aggregate shape properties

Aggregate Type		L	I	S	Shape Factor	Aspect Ratio	Sphericity	Flatness	Elongation	Roundness			Roundness		
										Top View	Side View	Average	Top View	Side View	Average
M1 n=60	Mean	1.880	1.548	0.575	0.338	1.217	0.632	0.373	0.831	1.199	3.067	2.133	0.836	0.564	0.700
	SD	0.336	0.243	0.124	0.051	0.130	0.045	0.062	0.087	0.053	4.380	2.198	0.035	0.179	0.095
M2 n=60	Mean	2.457	1.185	0.901	0.548	2.377	0.563	0.868	0.489	1.496	1.253	1.375	0.674	0.801	0.738
	SD	0.526	0.232	0.201	0.168	2.586	0.068	0.905	0.084	0.149	0.076	0.099	0.062	0.047	0.047
M3 n=60	Mean	1.411	1.306	1.017	0.751	1.083	0.875	0.780	0.931	1.179	1.218	1.199	0.849	0.823	0.836
	SD	0.262	0.231	0.205	0.078	0.101	0.055	0.081	0.085	0.047	0.072	0.048	0.032	0.044	0.030
M4 n=60	Mean	1.883	1.424	0.868	0.532	1.343	0.704	0.612	0.771	1.287	1.328	1.307	0.783	0.760	0.771
	SD	0.421	0.282	0.279	0.134	0.268	0.096	0.150	0.139	0.113	0.138	0.091	0.064	0.073	0.050

Note: n = Number of particles analyze

presented in Figures 12, 13, 14, 15, 16 and 17. It can be seen in Figure 12 the positive (R^2=0.82) correlation among the shape factor and compressive strength. Increasing in shape factor amount has direct effect on compressive strength increasing. There is a positive correlation (R=0.89) between sphericity and compressive strength. It means that lower sphericity index resulted lower values of compressive strength (Figure 13). It can be seen in Figure 14, the best positive (R^2=0.977)

Figure 11: The Relationship Between Compressive Strength and Shape of Aggregates

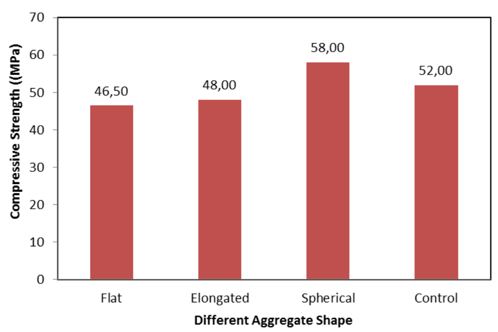


Figure 12: The Correlation Between Shape Factor and Compressive Strength

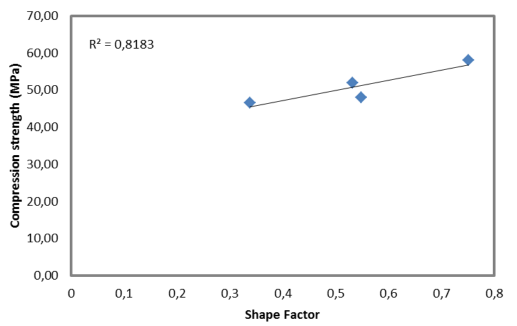


Figure 13: The Correlation Between Sphericity and Compressive Strength

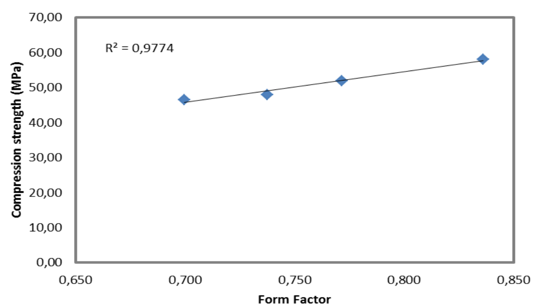


Figure 14: The Correlation Between Form Factor and Compressive Strength

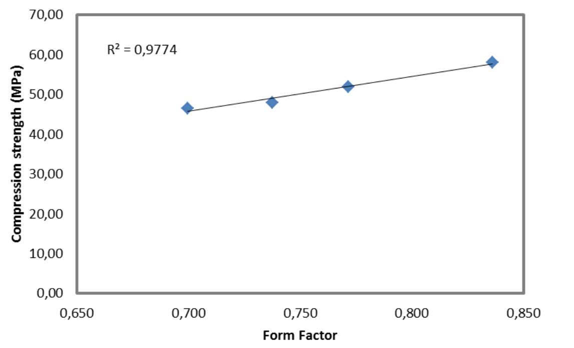


Figure 15: The Correlation Between Shape Factor and UPV

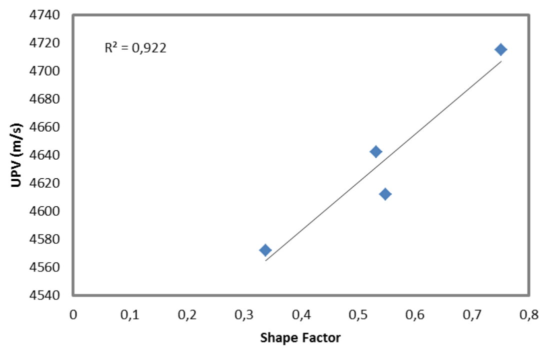
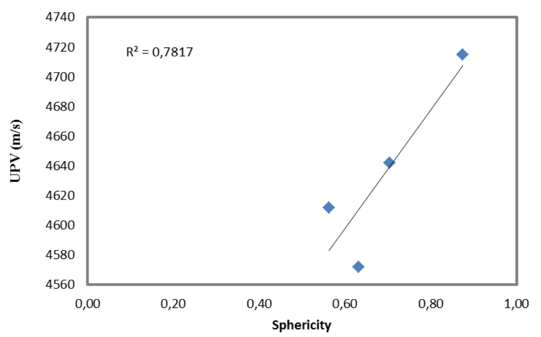
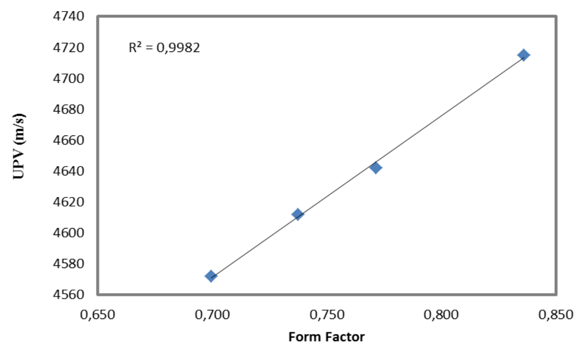


Figure 16: The Correlation Between Sphericity and UPV



correlation has been existed among the form factor and compression strength.

Figure 17: The Correlation Between Form Factor and UPV



It can be seen in Figure 15 the positive (*R*=0.92) correlation among the shape factor and UPV amounts. Increasing in shape factor amount has direct effect on UPV. There is a positive correlation (R^2=0.78) between sphericity and UPV. It means that lower sphericity index resulted lower values of UPV and it is similar to the correlation between sphericity and compressive strength (Figure 16). It can be seen in Figure 17, the best positive (R^2=0.998) correlation has been existed among the form factor and UPV.

CONCLUSION

A study was undertaken to investigate the effect of different type of aggregates on the compressive strength of concrete by a means of aggregate shape indexes such as aspect ratio, elongation, flatness, form factor, roundness, shape factor, and sphericity. The concrete produced with natural aggregate and four different type of coarse aggregate was used in the tests. These aggregates were selected as flat, elongated, spherical and mixed shape. The shape properties were determined by digital image processing with two different views of aggregates. The following conclusions are made based on the test results and on the discussion presented in this study:

- The image analyzer was shown to be a useful tool for quantifying the morphological characteristics of coarse aggregate.
- The test results indicated that a strong correlation between the some shape indexes of aggregate and compressive strength of concrete.
- The particle shape factors were shown to be an adequate measure of the combined contribution of some particle shape factor such as flatness, elongation and sphericity to the compressive strength of an aggregate.
- Spherical particles were desirable for increased compressive strength, UPV, unit weight and slump values of concrete. The more nearly spherical the aggregate, the higher mentioned values.

It should also be pointed out that further studies on the aggregate shape properties with digital image processing are needed to make more reasonable judgments. Further studies will be subjected that the mechanical properties of concrete such as compressive strength can be predicted by using digital image processing.

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