Tikrit Journal of Engineering Sciences (2024); 31(2): 60-71
DOI: http://doi.org/10.25130/tjes.31.2.6

IRAQI Academic Scientific Journals

ISSN: 1813-162X (Print); 2312-7589 (Online)

Tikrit Journal of Engineering Sciences

available online at: http://www.tj-es.com

TJES Tikrit Journal of Engineering Sciences

Effect of High-Density Packing Recycled Aggregate on Concrete Strength Properties

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Keywords:
Concrete Debris; Construction Waste; High-Density Packing Aggregate; Recycled Aggregate.

Highlights:

- *Study the effect of high-density packing recycled aggregate on concrete strength properties.*
- *Materials performance was considered in experimental manners.*
- *The aim to create a comfortable human environment in this study was done by recycling construction materials.*

ARTICLE INFO

Article history:

Received	21 Mar.	2023
Received in revised form	11 June	2023
Accepted	25 Nov.	2023
Final Proofreading	04 Feb.	2024
Available online	04 May	2024

Citation: Albo Ali WS, Abdulrahman MB, Alani AA, Lesovik RB. **Effect of High-Density Packing Recycled Aggregate on Concrete Strength Properties**. *Tikrit Journal of Engineering Sciences* 2024; **31**(2): 60-71.
http://doi.org/10.25130/tjes.31.2.6

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Abstract: As many residential homes and structures were destroyed or badly damaged because of the military battle in Iraq, it is critical to recycle construction debris widely in the rebuilding and decoration of buildings and infrastructure. This battle resulted in the buildup of massive construction debris, and recycling this waste allows for a cleaner environment. Recycling the construction waste of various installations is an urgent need to decrease the consumption of natural materials and landfills of construction waste, and as a result reduce the environmental pollution. Therefore, this study is a local focus on using concrete debris to obtain high packing density recycled coarse and fine aggregates in various fractions of (0.16 mm - 10 mm) by selecting high-density packing materials that was developed by Kharkhadin A.N in laboratories of Belgorod State Technical University in Russia to preparing of reference mix from ordinary density recycled aggregate. The new concrete samples for two concrete mixtures were prepared, to identify and study the important specifications. Models of cubes and standard prisms were prepared to evaluate the compressive strength and the splitting tensile strength. Also, the modulus of rupture and the unit weight were conducted. The results indicated an increase in the concrete's mechanical properties using the high-packing density recycled aggregate. The obtained compressive strength, splitting tensile strength and modulus of rupture were (49) MPa, (3.6) MPa, and (7.1) MPa compared with a reference mix (39) MPa, (3.3) MPa and (6.3) MPa, respectively. The reference mix corresponding properties were (39) MPa, (3.3) MPa, and (6.3) MPa, respectively. Also the values of an oven-dry density were (2340) kg/m^3 compared with the reference mix (2260kg/m^3). These results proved that increasing the packing density of recycled aggregate enhanced the concrete's strength properties.

تأثير الركام المعاد تدويرة عالي الكثافة على خصائص مقاومة الخرسانة

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الخلاصة

نتيجة الصراع العسكري في العراق، فان العديد من المنازل والمباني السكنية دمرت بشكل كامل أو لحقت بها أضرار جسيمة، لذلك من المهم للغاية إعادة تدوير هذه النفايات على نطاق واسع واستخدامها في إعادة إعمار وتزيين المباني والمنشآت، ومن ناحية أخرى أدى هذا الصراع إلى تراكم كميات هائلة من مخلفات البناء، إن اعادة تدوير المخلفات الإنشائية للمنشآت المختلفة ضرورة ملحة لتقليل استهلاك المواد الطبيعية ووتقليل طمر النفايات الإنشائية، وبالتالي تقليل التلوث البيئي. لذلك، فإن هذه الدراسة تركز محليًا على استخدام المخلفات الخرسانية للحصول على ركام ناعم وخشن معاد تدويرة ذو كثافة تعبئة عالية بتدرج مختلف يتراوح بين (٠,١٦ ملم - ١٠ ملم) باستخدام طريقة اختيار مواد التعبئة عالية الكثافة التي طورها العالم الروسي خرخادن اناتولي في مختبرات جامعة بيلغورود التقنية في روسيا، بالإضافة إلى ذلك تم عمل خلطة خرسانية مرجعية باستعمال الركام المعاد تدويرة ذو الكثافة الطبيعية. ولغرض تحديد ودراسة الخصائص المهمة للخرسانة المنتجة، تم تحضير عينات خرسانية جديدة لخلطتين خرسانيتين، وتم تحضير نماذج المكعبات والمنشورات المعيارية، لتقييم مقاومة الانضغاط ومقاومة الشد على التوالي. بالإضافة إلى ذلك تم حساب معامل الكسر الكثافة الظاهرية للمكعبات الخرسانية. أشارت نتائج الاختبارات إلى زيادة في الخواص الميكانيكية للخرسانة في حالة استخدام الركام المعاد تدويره بكثافة التعبئة العالية ، وكانت قيم الخواص الميكانيكية لها : مقاومة الانضغاط وقوة الشد ومعامل الكسر تساوي (٤٩) ميجا باسكال ، (٣,٦) ميجا باسكال و (٧,١) ميجا باسكال مقارنة بنتائج الخلطة المرجعية التي تساوي (٣٩) ميجا باسكال ، (٣,٣) ميجا باسكال و (٦,٣) ميجا باسكال على التوالي ، كما وجد ان الكثافة الوزنية الجافة للخلطة عالية الكثافة تساوي (٢٣٤٠) كجم/م٣ مقارنة مع كثافة الخلطة المرجعية التي تساوي (٢٢٦٠ كجم/م٣) . أكدت هذه النتائج أن زيادة كثافة التعبئة للركام المعاد تدويره أدى إلى تعزيز خصائص المقاومة للخرسانة المنتجة.

الكلمات الدالة: الحطام الخرسائي، الركام المعاد تدوير، الركام عالي الكثافة، مخلفات البناء.

1.INTRODUCTION

Construction waste in the form of concrete debris resulted from military actions and the demolition of various objects. These wastes are dumped and accumulated annually in large quantities. They are very durable and decompose, causing an increasingly serious environmental pollution problem. The Scientists worldwide aim to create a comfortable human environment or optimize the "human-material– environment" [1-5]. In many countries natural aggregates deficiency increase transportation costs and shortage of dumping sites and causes environmental pollution, leading using of recycled aggregate as a replacement material in producing concrete [3]. The increased development rate significantly increased construction waste; meanwhile, natural raw materials are rapidly depleted. An alternative way to solve this problem is using concrete waste as a quality of techno genic raw materials [2, 5]. Rapid industrialization produces major difficulties all around the world, such as natural resources depletion and a massive amount of waste accumulation [6]. One solution to this challenge is using raw materials in the construction industry. Recycled construction waste can be obtained from demolished buildings, airport runways, bridge piers, and concrete roads [7]. Using recycled aggregates for concrete production entails crushing concrete debris to generate crushed stone of the desired size and quality, which frequently has higher water absorption, lower density than traditional aggregates, higher porosity, and low specific gravity [8]. Concrete recycling is important because it protects natural resources and recycles construction waste from old concrete. The concrete mixture's fine aggregate is necessary to create a rigid structural frame and involve it in work when a load is applied to a product or structure [9]. A fine aggregate of natural composition can be used or introduce the missing number of certain fractions (enrichment). Since many deposits' sands contain an insignificant amount of fractions – (2.5–5 mm), then to create a rigid structural frame, the concrete mixture must be enriched with a larger fraction [10]. A high-density aggregate packing is calculated to reduce the binder in concrete consumption. Because increasing the packing density of particles by 0.01 increases the building strength 03–5% [11, 12] it was also estimated that the total quantities of construction and demolition debris worldwide are (2-3) billion tons per year [13]. Singh and Sharma [14] reported some of the reasons that caused the increasing volume of construction debris:

1- Many old buildings, concrete pavements, and bridges are over-old. Their use has become limited due to suffering from deterioration, which cannot be repaired and needs to be demolished.
2- Demolition of concrete structures that do not serve the current need.
3- The need for new facilities for better economic growth.
4- The constructions collapse and turn into debris when exposed to some

natural disasters, such as earthquakes, hurricanes, and floods.

5- Sometimes, the debris is produced by man-made wars.

Forondistou, [15] reported that a reduction in the compressive strength of (4 – 14) % occurred in (RAC) compared to the natural aggregate concrete with the same composition. The study of Bernier et al. [16] found that when high-strength concrete was produced from low-strength recycled coarse aggregate, the compressive strength was about (39) %, i.e., lower than when high-strength concrete was produced from strengthened recycled coarse aggregate. Ravindrajah and Tam [17] reported that the indirect splitting tensile strength of (RACs) made with recycled coarse aggregate and natural fine aggregate was insignificantly different from that of natural aggregate concrete. Ravindrajah and Tam [17] reported that the indirect splitting tensile strength of (RACs) made with recycled coarse aggregate and natural fine aggregate was insignificantly different from that of natural aggregate concrete. Ikeda et al. [18] stated that the tensile strength of (RAC) was (25) % lower than that of the corresponding conventional concrete. Various researchers investigated the effect of recycled concrete aggregate on the modulus of rupture. Most of them found that it was the same or (20) % lower than the conventional concrete in the worst case. Acker [19] used a (100) % replacement of (RCA) and reported a (20) % reduction of the modulus of rupture. Al-Mutairi and Haque [20] concluded that when the (RCA) was used by (50) %, the modulus of rupture was (4.65) % lower, and with (100) % replacement, the same modulus of rupture was obtained. This work studies the effect of using recycled coarse and fine aggregates together with different fractions (5-20mm) for coarse aggregate and (0.16-5 mm) for fine aggregate extracted from concrete debris (raw materials) as high-packing density aggregate in the concrete mixture instead of normal aggregate. It was found that improving the overall structure obtained by increasing a high packing density of aggregate particles from (0.631 to 0.814) increased the concrete strength by (23%) compared with the reference concrete. The splitting tensile strength increased in splitting tensile strength compared to the reference concrete (2.44, 5.7) %. This study aims to get high-packing density recycled aggregate to produce new concrete with compressive strength ranging from 20 to 50 MPa and use it in reconstructing and restoring destroyed buildings and facilities. From the preceding, studies on the effect of density using recycled aggregates are few; therefore, this research paper presents a study in this direction.

2.TESTING PROGRAM

2.1.The Used Materials

2.1.1.Cement

Ordinary Portland cement, CEMI 42.5N (Belgorod cement), was used as a binder according to the Russian Cement Specifications (No. 10178-85 and No.30515-2013) [21, 22], as shown in Tables 1, 2, and 3.

Table 1 Chemical Composition of Clinker, %.

Parameter	Value	Standard according to code
CaO	66.2	-
SiO_2	22	-
Fe_2O_3	4.23	-
Al_2O_3	5.4	-
MgO	0.6	not more than 5%

Table 2 Mineralogical Composition of Clinker, %.

Parameter	Value	Standard according to code
C_3S	59	-
C_2S	18.8	-
C_3A	7.00	not more than 8.00
C_4AF	13.1	-

Table 3 Properties of Belgorod Portland Cement CEMI 42.5N.

Parameter	Value	Standard limit
Specific surface, m²/kg	330	-
Initial setting time, hr.	2.5	not earlier than 2
Final setting time, hr.	3.35	not later than 10
Binder strength, MPa :		
3 days		
-Tension	5.8	-
- compression	33.00	-
28 days		
-Tension	8.1	not less than 5.9
- compression	56.6	at least 49
Fineness of grinding	7.00	at least 8.5
Normal density,%	25.5	-
Sulfur oxide So_3,%	2.42	at leas and not mor 3.5
Chloride, Cl, %	0.002	not more than 0.1

2.1.2.Coarse and Fine Aggregates

The fine aggregate of concrete and quartz sand (deposit quarry) was used, with a roughness coefficient of 1.01, bulking density of 1495 kg/m³, specific gravity of 2640 kg/m³, and voids ratio of 47.8%, and humidity of 5.5%; this sand conforms to the Russian specification No. (8736-93) [23]. The coarse aggregate, crushed quartz stone (Lebedsky quarry), was used with a roughness coefficient of 6.2, bulk density of 1450 kg /m³, a specific gravity of 2670 kg/m³, and a moisture content of 2%. This stone conforms to the Russian specification No. (8269.0-97) [24].

2.1.3.Recycled Aggregate

Recycled aggregate (fine and coarse aggregate) extracted from concrete debris was used as fine and coarse aggregate of the main mixtures. The recycled coarse aggregate was used, with a roughness coefficient of 6.85, a bulking density of 1450 kg/m3, and a specific gravity of 2520 kg/m3. The recycled fine aggregate was used with a roughness coefficient of 2.49, bulk density of 1600 kg /m3, a specific gravity of 2520 kg/m3, and a moisture content of 5%. Fig. 1 shows the grain composition of concrete debris fragments. The major mineral of fine aggregate in the form of concrete scrap crusher screening was calcite, the content of which was about (38.28%), quartz (25.9%), kaolinite (28.77%), and dicalcium silicate (belite) (7.05%), as shown in Fig. 2.

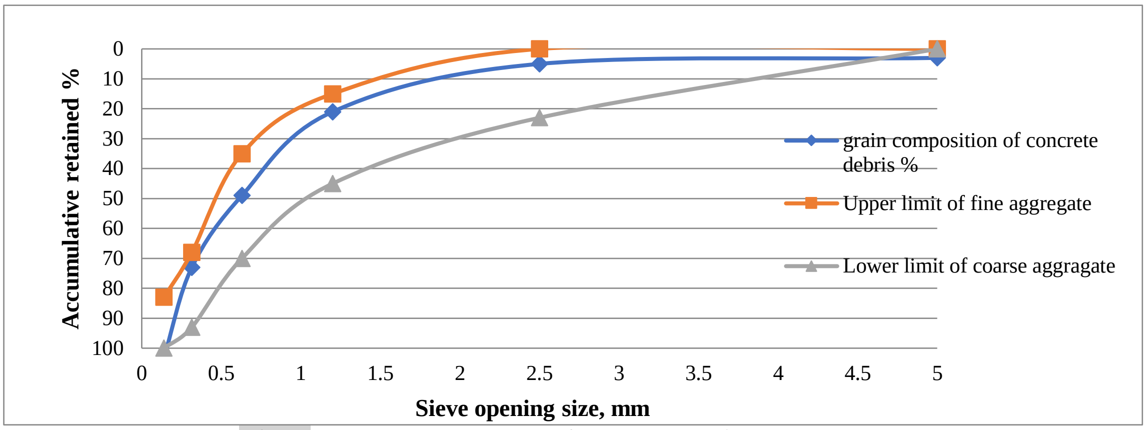
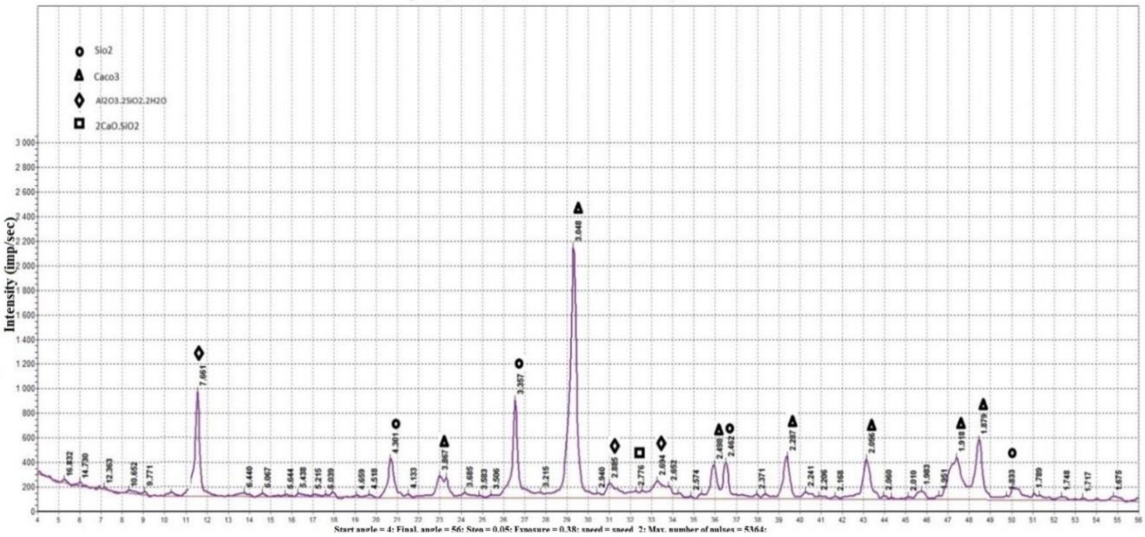


Fig. 1 Grain Composition of Concrete Debris Fragments.



Start angle = 4, Final angle = 56, Step = 0.05, Exposure = 0.38, speed = speed_2 and Max. Number of pulses = 5364

Fig. 2 X-ray Diffraction Pattern of Crushing Concrete Debris.

3.EXPERIMENTAL PROCEDURE

Calculating the grain composition of concrete using concrete debris was conducted by the Kharkhadin method [11]. Concrete efficiency increased by raising the packing density of the aggregate obtained from the concrete debris of demolished buildings and structures. A method for obtaining crushed stone and sand from concrete debris has been developed. The crushed fractions were sifted using standard sieves and sorted into large fractions (10-20 and 5-10 mm) and fine fractions (2.5 - 5, 1.25 - 2.5, 0.630 - 0.315 and 0.315 - 0.16 mm) as shown in Fig. 3. To calculate the packing density of recycled aggregate extracted from concrete debris, the steps below must be followed:

1- Crushing the concrete debris with a crusher. Then, the crushed fractions were sifted using standard sieves and sorted into large fractions (10-20 and 5-10 mm) and fine fractions (2.5 - 5, 1.25 - 2.5, 0.630 - 0.315, and 0.315 - 0.16 mm), as shown in Fig. 3.

2- Calculating the packing density of each fraction using Eq. (1):

$$\eta_n = \frac{\gamma_n}{\rho} \quad \textbf{(1)}$$

3- Calculating the required fraction number and its ranges to obtain high packing density, where a suitable class "m" of the particle distribution system in a high-density mixture is preliminarily determined via selection, determining the discontinuity in their average particle sizes of the biggest fraction with their packing density using Eq. (2):

$$\frac{d_n}{d_1} = \left(\frac{2.549}{10\eta_1}\right)^{\frac{m(n-1)}{3}} \quad (2)$$

4- The computation was based on estimating the grain distribution related to the average distances between each component of the high-density mixture. Initially, a high bulk density was chosen; then, the blocks of filling the volume with aggregate grains were calculated from Eq. (1). The filling density of granules with substantial fractions of aggregates was known, ranging from $\eta_1 = 0.6 - 0.56$ depending on the shape of their granules.

5- Most of the aggregate is usually considered $G_1 = 100$ mass. parts; then, the mass fraction of each subsequent fraction is calculated from:

$$G_n = (1-\sigma_{n-1}) \times \frac{\eta_n}{\sigma_{n-1}} \times \beta_n \sum_{i=1}^{n-1} G_i \quad (3)$$

Where σ_{n-1} is the packing density of grains in a mixture consisting of (n-1) fractions, so for n=2 and $\sigma_1 = \eta_1$. To reduce consuming each fraction in rigid polydisperse mixtures (β_n = 1), Eq. (4) is used with consuming fine fractions reduced to a minimum and the degree of filling of free volume in them in the form:

$$G_n = (1-\sigma_{n-1}) \times \left(\frac{\eta_n}{\sigma_{n-1}}\right)^{\frac{(n+1)}{2}} \times \beta_n \sum_{i=1}^{n-1} G_i \quad (4)$$

$$\sigma_n = \frac{\gamma_n}{\rho} \quad (5)$$

$$\sigma_{na} = \sigma_{nn} \times \beta_n^{\frac{1}{n}} \quad (6)$$

Alternatively, calculated by the formula:

$$\sigma_n = \sigma_{n-1} + \left(\frac{1-\sigma_{n-1}}{\beta_n}\right) \times X_n \quad (7)$$

$$\text{where } X_n = \frac{\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} \Psi_{ij}^m}{n(n-1)/2} \quad (8)$$

The value Ψ_{ij}^m for bimodal packages based on (m) or on the relative particle size d_n/d_1, as shown in Table 5 where the value of the minimal amount of fine aggregate at $\beta_2 = (\eta_1/\sigma_2)^{1/(n-1)}$. The results of the sieve analysis of the concrete debris' grain composition are shown in Table 4. The grain composition of produced recycled aggregate created from concrete debris has fewer fine fractions, does not correspond to creating high density, and also does not fit into the ideal zone of grain compositions. The results of the sieve analysis of the grain composition of the concrete debris are shown in Table 4. The grain composition of produced recycled aggregate created from concrete debris has less fine fractions, does not correspond to the creation of high density, and also does not fit into the ideal zone of grain compositions. Increasing the efficiency of recycled aggregate by sieving concrete debris isolates the fine fractions that negatively affect the produced recycled concrete's strength because they are considered undesired loose fine materials [23].

(a) (b) (c) (d) (e)

Fig. 3 Recycling Process of the Concrete Wastes from Demolished Home in Iraq Carried Out in Russia According to Russian Specifications [23]: (a) Demolished Home, (b) Concrete Wastes, (c) Crushing Machine, (d) Sieving Work, and (e) Recycled Aggregate.

Table 4 Composition of a Grain of Concrete Debris Fragments.

Parameter	Size of sieve opening, mm							Passing through a sieve No. 0.16
	10	**5**	**2.5**	**1.25**	**0.63**	**0.315**	**0.16**	
Remaining on the sieves, g	770	200	50	160	280	240	280	20
Remaining on sieves , %	38.5	20	5	16	28	24	28	0.2
Accumulative,%	38.5	20	5	21	49	73	101	100
Bulk density, kg/m3	12060	1200	1287	1180	1200	1285	1370	1386
Specific gravity	2520	2520	2520	2520	2520	2520	2520	2520
Packing density	0.500	0.476	0.511	0.468	0.476	0.51	0.544	0.55
Size Modulus	2.49							

Table 5 The Degree of Filling of Free Volume in a Layer of Large Molecules with Small Particles Depends on the Class of Systems m and Their Relative Size in Binary Packages [11].

m	**< 1**	**1**	**2**	**3**	**4**	**4.5**	**5**
Ψ_{ij}^{m}	$\varepsilon_i^3\eta_i^3$	$\varepsilon_i^2\eta_i^3$	$\varepsilon_i^2\eta_i^2$	$\varepsilon_i^2\eta$	ε_i^2	$\varepsilon\eta_i^2$	ε_i^2/η
$\frac{d_n}{d_1}$	≤ 1	0.73	≤ 0.54	≤ 0.39	0.29	0.25	0.21
Ψ_{ij}^{m}	0.011	0.033	0.052	0.080	0.123	0.148	0.189
m	6	7	8	9	10	11	12
Ψ_{ij}^{m}	$\varepsilon\eta$	$\varepsilon_i^2\eta_i^2$	ε	η_i^2	ε_i/η_i	$1-\eta_i^2$	η_i
$\frac{d_n}{d_1}$	≤ 0.15	≤ 0.4	≤ 0.08	≤ 0.06	≤ 0.04	≤0.033	≤ 0.024
Ψ_{ij}^{m}	0.227	0.290	0.350	0.422	0.539	0.578	0.65

The fraction (2.5–5 mm) and other fractions of coarse and fine aggregates obtained by crushing concrete debris and subsequent sieving have a higher flaky grain, i.e., (30–40%) [25]. The method for calculating and selecting fractions from screenings of the crushing fragments product of destroyed buildings and structures in Iraq to obtain a high-density mixture is that the theoretical amount of each fraction is calculated according to the above equations, and they are selected from the available dispersed raw materials dispersed into narrow fractions [26].

4.CALCULATE THE MIX FRACTIONS FOR VARIOUS NUMBERS OF SUBSTANCES

Experimental grain packing density of concrete scrap from fragments of destroyed buildings and structures in Iraq $\mu_1 = 0.5$. Substituting into the formula, the value μ_1 and the average grain size $d_{average} = (10\times5)$ ½ = 7.07 mm [11] for a different distribution class m = 1 - 12, a system of distributions of the corresponding discontinuity class in their granulometric composition will be obtained. For a wide range of fractions, the acceptable m = 3, so:

$$d_n/ d_1 = (2.549/10\ \eta_1)^{n-1} = (0.2549/0.5)^{n-1} = 1,\ 0.50, 0.25, 0.132, 0.068, 0.0344, 0.0176, 0.009, 0.0046$$

The calculation is completed when the average particle size of the fine fraction $d_n = (d_n / d_1)\, d_1$ mm = 0.0176×7.07 = 0.124 mm is indicated by the recommended concrete aggregate size, d_n= 0.14 - 0.1 mm. According to d_n / d_1, the grain sizes for each narrow part will be equal to:

d_n= 10 - 5 mm (1, 0.50, 0.25, 0.132, 0.068, 0.0344, 0.0176, 0.009, 0.0046) =10 – 5, 5 - 2.5, 2.5 - 1.25, 1.32 - 0.66, 0.68 - 0.34, 0.344 - 0.172, 0.176 - 0.088, 0.09 - 0.045, 0.046 - 0.023 mm.

Each granular part (fraction) is selected on standard sieves, and the packing density (η) of their granules is determined by the bulk density and specific gravity using Eq. (1) will be equal to:

η_1=0.50, η_2=0.476, η_3=0.511, η_4=0.468, η_5=0.476, η_6=0.51, η_7=0.544, for each fraction was determined experimentally.

When calculating the amount of each fraction to obtain the densest packing of the mixture, any arbitrary value (G_1) of the volume fraction is used, for example, 1 kg, 10 kg, 100 kg, or 100 mass. parts. Then the second fraction and each subsequent fraction are calculated considering the granularity factor according to the Eq. (3). Taking 100 mass.part. for the first large fraction, for a mixture of class m = 3, the amount of the second fraction aggregates, according to Eqs. (3 and 4), will be required:

At $\beta_2 = 1$, $G_n = (1-\sigma_{n-1}) * \left(\frac{\eta_n}{\sigma_{n-1}}\right) . \beta_n \sum_{i=1}^{n-1} G_i$

And $G_n = (1-\sigma_{n-1}) * \left(\frac{\eta_n}{\sigma_{n-1}}\right)^{\frac{(n+1)}{2}} * \beta_n \sum_{i=1}^{n-1} G_i$

where, $\sigma_{n-1} = \eta_{n-1}$, $G_1 = 100\ mass.part \sigma_{n-1} = \eta_1 = 0.5$

Respectively, :

$G_2 = (1-\eta_1) * \left(\frac{\eta_2}{\eta_1}\right) * \beta_2 \sum_{i=1}^{n-1} G_1 =$ (1-0.5) (0.476/0.5)*1*100 = 48 mass.part.

or the minimum quantity of fractions is.

$G_n = (1-\eta_1) * \left(\frac{\eta_2}{\eta_1}\right)^{\frac{(n+1)}{2}} . \beta_2 \sum_{i=1}^{n-1} G_1 =$ (1-0.5) $(0.476/0.5)^{3/2}$*1*100 = 46 mass.part.

Packing density (σ_2) of grains in a mixture consisting of the first two fractions, where $\sigma_1 = \eta_1$, will equal :

At β_2 = 1 and ε_2 = (1- η_2) = (1-0.476) = 0.524;

$\sigma_2 = \sigma_1 + (1-\sigma_1) * \left(\frac{X_2}{\beta_2}\right) = 0.5 + (1-0.5)\varepsilon_2^2\eta/$ β_2=0.5+ (1- 0.5)*$(0.524)^2$*(0.476)/1=0.565

At $\beta_2 = \frac{\sigma_{n-1}}{\eta_n} = \frac{\sigma_1}{\eta_2}$ = (0.5/0.476) = 1.050; σ_2 = 0.5 + 0.5*0.524^{2}* 0.476 /1.050 = 0.538

for class m = 3 particle distribution systems in the mixture $X_2 = \varepsilon_2^{\,2}\eta_2$, Table 5.

The required amount of the third fraction will be required: at β_3 =1, $G_3 = (1-\sigma_2).\left(\frac{\eta_3}{\sigma_2}\right) \times \beta_3 \sum_{i=1}^{n-1} G_2$ =0.5+ (1- 0.538). (0.51/0.538)×1×(100+48) = 65 mass.part.

or the minimum quantity of fraction will be.

G_3= (1-0.538) $(0.51/0.538)^{4/2}$×1×(100+46) = 61mass.part.

The calculating the Xi value is determined manually according to the grain distribution scheme in the voids of the granular layer.

$X_3 = (\varepsilon_2^{\,2}\eta_2 + \varepsilon_3^{\,2}\eta_3 + \varepsilon_3\,\eta_3)$ /3(3-1)/2 = (0.524^2×0.476 +0.49^2×0.51 +0.49×0.51)/3=0.168.

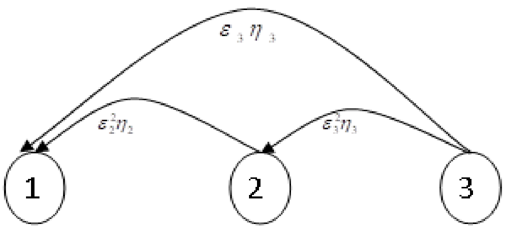


Fig. 4 Distribution of Grains in a Mixture Consisting of 3 Fractions.

The packing density of grains in a mixture consisting of the first three fractions will be equal to:

$\sigma_3 = \sigma_2 + (1-\sigma_2)X_3/\beta_3$, $\beta_3 = \frac{\sigma_{n-1}}{\eta_n}$ = 0.538/0.51= 1.055

σ_3 = 0.538+(1-0.538) 0.168/1.055 = 0.612

At $\beta_3 = \frac{\sigma_2}{\eta_3}$ = (0.538/0.51) =1.055 and at β_3 = ($\frac{\sigma_2}{\eta_3}$ $)^{1/2}$ = $(0.538/0.51)^{0.5}$=1.027

σ_3 = 0.538+(1-0.538) 0.168/1.055=0.612

σ_3 = 0.538+(1-0.538) 0.168/1.027=0.613

Take a smaller value σ_n and $\sigma_3 = 0.612$.

To calculate the required amount of the fourth and subsequent fractions of grains in a mixture of four or more fractions, a distribution with m = 3 is considered. Number of bilateral bonds (two-way distribution) of molecules in spaces separated by a layer *m=n (n-1)/2=4.3/2=6*, where n is the number of all fractions in the mixture, considering account each subsequent fraction of the mixture.

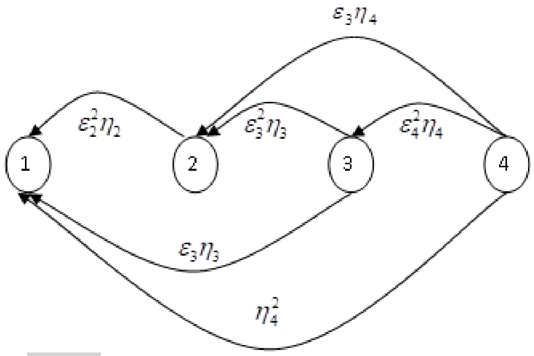


Fig. 5 Distribution of Grains in a Mixture Consisting of 4 Fractions.

The distribution of particles in a 4-fraction mixture is calculated using X_4 according to the scheme, and then β_4:

$X_4 = (\varepsilon_2^{\,2}\eta_2 + \varepsilon_3^{\,2}\eta_3 + \varepsilon_4^{\,2}\eta_4 + \varepsilon_3\,\eta_3 + \varepsilon_4\,\eta_4 + \eta_4^{\,2})$ /[4(4-1)/2] = (0. 524^2*0. 476 +0.49^2*0.51 + 0.532^2*0.468 + 0.49*0.51 + 0. 532*0. 468 + 0. 468^2)/6 = 0.184

At $\beta_4 = \left(\frac{\sigma_3}{\eta_4}\right)^{1/n-1}$ = $(0.612/0.468)^{1/3}$ =1.093, β_4 = $\left(\frac{\sigma_3}{\eta_4}\right)$ = (0.612/0.468) =1.31.

At β_4 =1

G_4= (1-0.612) (0.468/0.612)*1*(100+48+65) = 63 mass.part.

or, G_4= (1-0.612) $(0.468/0.612)^{5/2}$*1*(100+46+61) = 41 mass.part.

At $\beta_4 = \frac{\sigma_3}{\eta_4}$ = (0.612/0.468) =1.31, and at β_4 = ($\frac{\sigma 3}{\eta_4}$ $)^{1/3}$= $(0.612/0.468)^{0.5}$ =1.145

σ_4 = 0.612+(1-0.612) 0.184/1.31=0.666

σ_4 = 0.612+(1-0.612) 0.184/1.145=0.674

imagining the distribution of grains in a 5-fractional mixture:

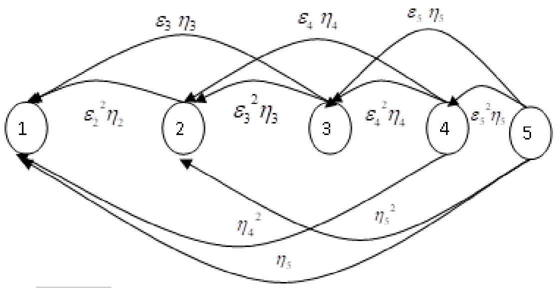


Fig. 6 Distribution of Grains in a Mixture Consisting of 5 Fractions.

$$X_5 = (\varepsilon_2{}^2\eta_2 + \varepsilon_3{}^2\eta_3 + \varepsilon_4{}^2\eta_4 + \varepsilon_5{}^2\eta_5 + \varepsilon_3\ \eta_3 + \varepsilon_4\ \eta_4 + \varepsilon_5\ \eta_5 + \eta_4{}^2 + \eta_5{}^2 + \eta_5\ ) \quad /[5(5-1)/2]$$

=(0.524²*0.476+0.49²*0.51+0.532²*0.468+0.524²*0.476+0.49*0.51+0.532*0.468+0.524*0.476+0.468²+0.476² +0.476)/10=0.219.

At β_5 = 1, G_5= (1-0.666) (0.476/0.666)*1*(100+48+65+63) = 66 mass.part.

G_5= (1-0.674) $(0.476/0.674)^{6/2}$*1*(100+46+61+41) = 28 mass.part.

At $\beta_5 = \dfrac{\sigma_{n-1}}{\eta_n}$, $\beta_5 = \left(\dfrac{\sigma_4}{\eta_5}\right)$ = (0.666/0.476) =1.4, $\beta_5 = \left(\dfrac{\sigma_4}{\eta_5}\right)^{1/n-1}$ = $(0.674/0.476)^{1/4}$ =1.1,

σ_5 = 0.666+(1-0.666) 0.219/1.4=0.718

σ_5 = 0.674+(1-0.674) 0.219/1.1=0.739.

Due to the cumbersomeness of the grain distribution scheme in a mixture of six and seven fractions, they were omitted. The number of bimodal bonds in a mixture of six fractions will equal n (n-1)/2 = 6(6-1)/2 = 15.

$$X_6=(\varepsilon_2{}^2\eta_2 + \varepsilon_3{}^2\eta_3 + \varepsilon_4{}^2\eta_4 + \varepsilon_5{}^2\eta_5 + \varepsilon_6{}^2\eta_6 + \varepsilon_3\ \eta_3 + \varepsilon_4\ \eta_4 + \varepsilon_5\ \eta_5 + \varepsilon_6\ \eta_6 + \eta_4{}^2 + \eta_5{}^2 + \eta_6{}^2 + \eta_4\ + \eta_5\ + \eta_6\ ) /[5(5-1)/2],$$

X_6=(0.524²*0.476+0.49²*0.51+0.532²*0.468+0.524²*0.476+0.49²*0.51+0.49*0.51+0.532*0.468+0.524*0.476+0.49*0.51+0.468²+0.476²+0.51²+0.468+0.476+0.51)/15=0.253.

At β_6 = 1, G_6= (1-0.718) (0.51/0.718)*1*(100+48+65+63 + 66) = 69 mass.part.

Or, G_6= (1-0.739) $(0.51/0.739)^{7/2}$*1*(100+46+61+41+28) = 20 mass.part.

At $\beta_6 = \dfrac{\sigma_{n-1}}{\eta_n}$, $\beta_5 = \left(\dfrac{\sigma_5}{\eta_6}\right)$ = (0.718/0.51) =1.4,

при β

$++6_6 = \left(\dfrac{\sigma_5}{\eta_6}\right)^{1/n-1}$ = $(0.739/0.51)^{1/5}$ =1.08 ,

σ_6 = 0.718+(1-0.718) 0.253/1.4 =0.769

σ_6 = 0.739+(1-0.739) 0.253/1.08=0.8.

When the seventh fraction is introduced into a mixture consisting of six fractions, the number of bimodal bonds in it will be: n (n-1) / 2 = 7(7-1)/2=21,

$$X_7 = (15\ X_6 + \varepsilon_7{}^2\eta_7 + \varepsilon_6\ \eta_6 + \varepsilon_7\ \eta_7 + \eta_7{}^2 + \eta_7\ + \eta_7\ ) \quad /21=$$

(15*0.253+0.456²*0.544+0.49*0.51+0.456*0.544+0.544²+0.544+0.544)/21=0.276

At β_7 = 1, G_7 = (1-0.769) (0.544/0.769)*1*(100+48+65+63 + 66+69) = 67 mass.part.

Or, G_7= (1-0.8) $(0.544/0.8)^{8/2}$*1*(100+46+61+41+28+20) = 13 mass.part.

At $\beta_7 = \dfrac{\sigma_{n-1}}{\eta_n}$, $\beta_7 = \left(\dfrac{\sigma_6}{\eta_7}\right)$ = (0.769/0.544) =1.41, $\beta_7 = \left(\dfrac{\sigma_6}{\eta_7}\right)^{1/n-1}$ = $(0.8/0.544)^{1/6}$ =1.07,

σ_7 = 0.769+(1-0.769) 0.276/1.41=0.814

σ_7 = 0.8+(1-0.8) 0.276/1.07=0.852.

The initial data for the calculation and its results are tabulated in Table 6.

Binder consumption by size from cement binder for 1 m³ of concrete mix at w / c = 0.45, will equal: V=1- σ_n /α_3 [11].

Where α_3 = 1.058 … 1.330. So V=1-[0.814/(1.058 to 1.330)] = 0.230 to 0.388 m³

The cement binder density paste for 1 m³ of concrete mix (ρ_t) at w / c = 0.45, will be equal to: $\rho_{t\,=}$ 1800 kg/m3

Thus: binder consumption by weight from cement binder for 1 m³ of concrete mix (ρ_t) at w / c = 0.45, will equal: 1800 kg = 414 to 698 kg/m3.

The increase in the concrete strength equal $\frac{0.814-0.631}{0.01}$.3% = 54.9%. The initial data for the calculation and its results are shown in Table 7. Note: 1- G_n-from Eq. (1) and 2- G_n-from Eq.(2). Table 8 shows the compressive strength splitting tensile strength and modulus of rapture values of concrete samples at 28 days age after curing for two different mixtures: conventional concrete and with high-density packing aggregate.

Table 6 Granulometric Composition of a High-Density Packing Mixture from Screenings of Concrete Debris Crushing.

Sieve fractions (mm)	Estimated part size (mm)	Grain packing density (η_n)	The composition of the mixture (mass.part)	Bulk density (γ) (kg/m3)	Density packaging (σ_n)
10 - 5	10 - 5	0.5	100	1260	0.50
5 - 2.5	5 - 2.5	0.51	48 (46)	1300	0.538
2.5 - 1.25	2.5 - 1.25	0.476	65(61)	1360	0.612
1.25 - 0.63	1.32 - 0.66	0.51	63(41)	1480	0.666
0.63 - 0.315	0.68 - 0.34	0.468	66(28)	1550	0.718
0.315 - 0.16	0.344 - 0.172	0.476	69(20)	1610	0.769
0.16 - 0.04	0.176 - 0.08	0.51	67(13)	1680	0.814

Table 7 Composition of High-Density Packing Concrete.

Sieve fractions(mm)	Aggregate weight for specimens measuring 10x10x10 cm (gm) Grain packing density (η_n)		Amount of cement (kg) for one cube measuring 10x10x10 cm	w/c- 52% (ml)	Bulk density (γ) (kg/m3)		Packing Density (σ_n)
	1*	2*					
10 - 5	615	413	444	230	1260	1260	0.50
5 - 2.5	289	198			1300	1320	0.538
2.5 - 1.25	332	244			1360	1400	0.612
1.25 - 0.63	221	240			1480	1500	0.666
0.63 - 0.315	166	248			1550	1600	0.718
0.315 - 0.16	129	256			1610	1650	0.769
0.16 - 0.04	98	251			1680	1720	0.814
Sum.	1850	1850					

Table 8 Properties of Concrete with High Packing Density Aggregate.

Parameter	ρ_c(kg/m³)	Cement (kg/m³)	Conc.debris (fra. 0.16-10 mm) (kg/m³)	w/c (%)	Packing Density (σ_n)	Compressive strength (MPa)	Splitting tensile strength (MPa)	Modulus of rapture strength (MPa)
Natural mixture	2260	486	1850	56	0,631	39	3.3	6.3
Dense mixture	2340	444	1850	45	0,814	49	3.6	7.1
Difference %	+3.54%	- 8.65	-	-19.6%	+29.8%	+25,6%	+9.1%	+12.7%

5.RESULTS AND DISCUSSION

5.1.Compressive Strength Test (f'c)

The concrete specimens' compressive strength was tested and compared according to (RU 10180: 2012) [27]. Fig. 7 shows that the compressive strength of the dense mix increased by 25.6% when high packing density coarse and fine aggregates were used, compared to the Natural mix. This result may be attributed to the reason that the aggregate used in Natural mix possessed a higher porosity and a lower density of about (29.8) % than high packing density recycled aggregates used in dense mix. Therefore, the lower density of the aggregate, which had the largest contribution to the concrete mass, reduced the concrete strength.

5.2.Splitting Tensile Strength Test

This test was conducted according to (RU 10180: 2012) [27] using a concrete prism with dimensions of (150 × 150 × 500) mm. Fig. 8 shows that the tensile strength of the dense mix increased by 9.1% when high packing density coarse and fine aggregates were used, compared to the Natural mix. The cracks in recycled aggregate concrete were entirely different from those in the natural aggregate concrete, where the fracture resulted in tensile stress in the very aggregate particles and the fracture in the matrix. On the other hand, in natural gravel concrete, the strength of the aggregate itself is usually high compared to the strength of the cement matrix. For this reason, failure in tension will rarely occur because of the aggregate's fracture itself; however, it is mostly due to the fracture matrix or the breakdown of the bond between the aggregate and the matrix. By inspecting, it was found that the failure plane in the natural mix in this work went directly through and around the recycled aggregate particles, while the opposite was found in the reference (natural aggregate) concrete.

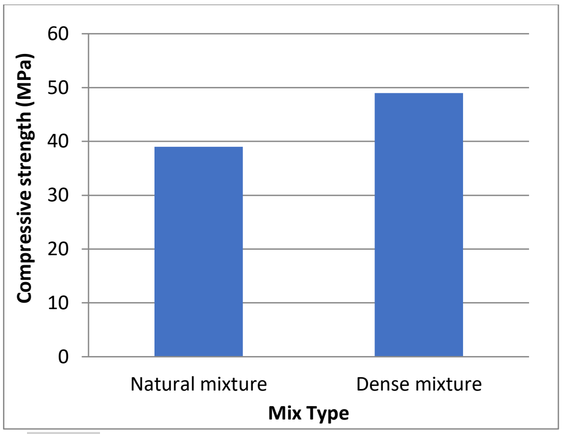


Fig. 7 Compressive Strength for the Mixes.

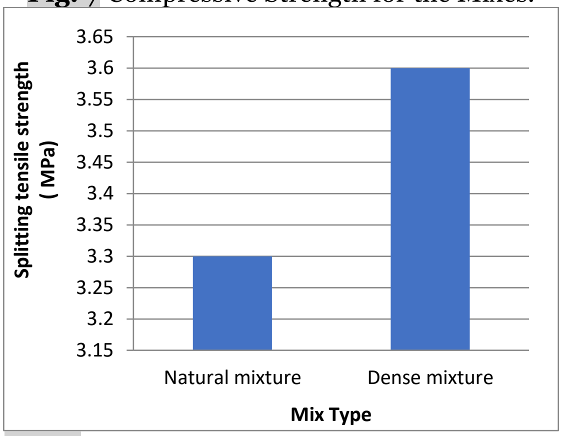


Fig. 8 Splitting Tensile Strength for the Mixes.

5.3.Modulus of Rupture Test

This test was conducted using four-point loading, i.e., a simple metal beam with a third-point loading. This test was carried out according to (RU 10180: 2012) [27]. Fig. 9 shows an increase in the Modulus of Rupture by 12.7% for dense mix in case of using high packing density coarse and fine aggregates if compared with the natural mix. This test is used to test the concrete cracking strength. This increase was caused by the old mortar attached to the gravel particles in the dense mix. Strong bond areas existed between the new and old mortars. Fig. 10 shows that the density and weight of the dense mix were greater by 3.5% than the natural mixture due to the difference in the specific weight between the normal recycled aggregate and the high-packing density recycled aggregate. The electronic microscope photos in Figs. 11 and 12 explained the contact zone and the bond between cement paste and aggregate. The bond in the dense mix is better than the bond in the natural mix due to using high-density aggregate in a dense mix. Figures 7 to 11 show that the dense mix strength was more than the strength of the natural mix because of the high packing density of the used recycled aggregate, which increased from 0.5 to 0.814, increasing the concrete's density since the filling density of particles increasing by 0.01, an increase in the strength of the building was observed by 3–5% [11]. Many researchers have proved that recycled aggregates from well-known and high-quality concrete produce concrete with similar compressive strength, if not higher, than natural aggregate concrete [28-31].

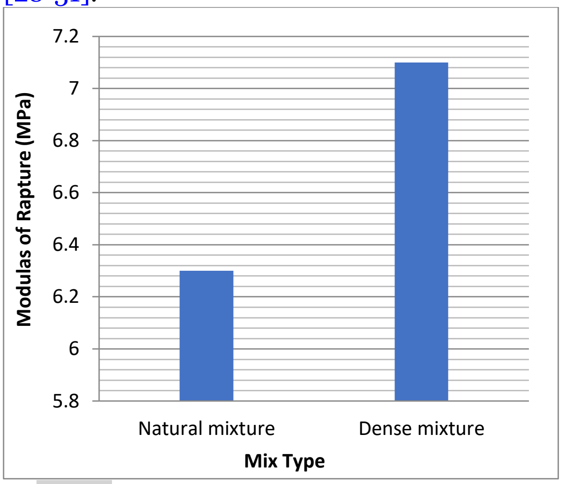


Fig. 9 Modulus of Rupture for the Mixes.

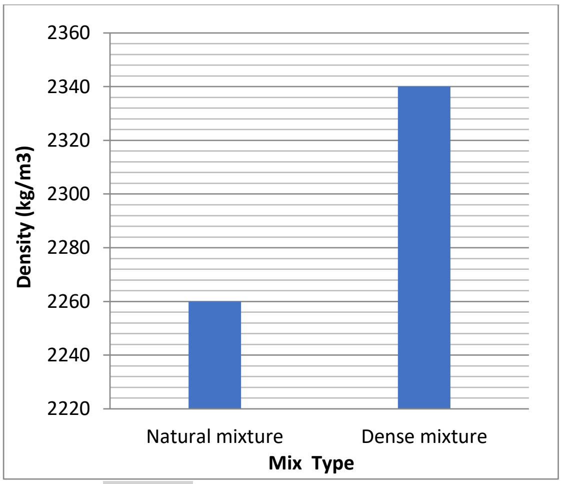


Fig. 10 Density for the Mixes.

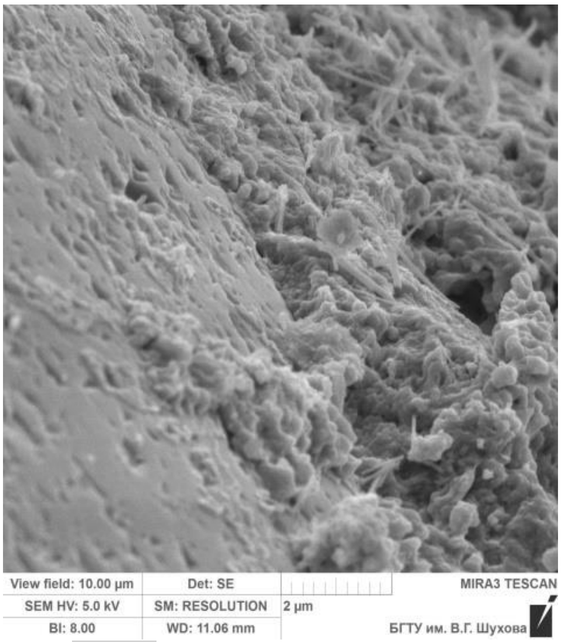


Fig. 11 Contact Zone in Dense Mix.

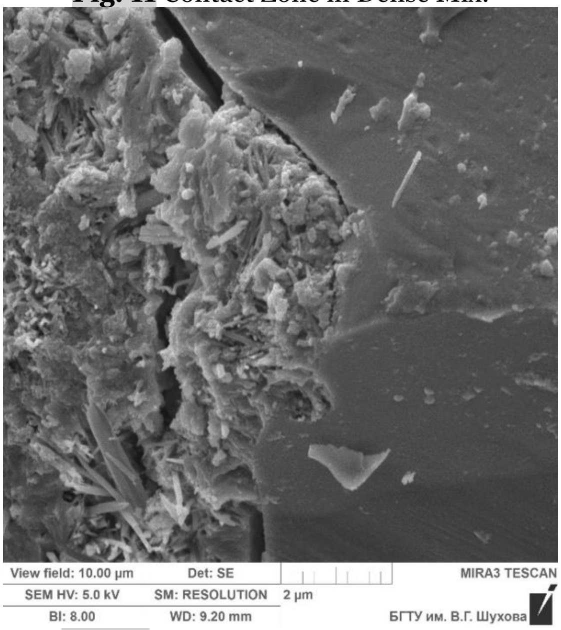


Fig. 12 Contact Zone in Natural Mix.

6.CONCLUSIONS

The following conclusions are obtained from the experimental results of the tested samples:

1- The simplest way to increase the packing density of particles in a mixture of recycled aggregate from concrete debris was inserting into this mixture particles of different fractions (up to 7 fractions), increasing the packing density of recycled aggregate by 29.8%.
2- Increasing the packing density of the used recycled aggregate enhanced the concrete mixture efficiency, increasing the produced concrete's strength properties, such as compressive strength, tensile strength, modulus of rapture, and concrete density.
3- The results showed that the water demand and binder consumption

resulting from the dense mix were less than the results for the natural mix by 19.6% and 8.65%, respectively.

4- The study proved that high-density recycled aggregate was reliable for producing concrete and can be used in reconstruction works; also, it will reduce the environmental impact and pollution.

5- Economically, the study showed that the cost of producing (1 m^3) of recycled aggregate concrete (dense mix) was less than that for natural mix by 29.7% due to the low costs of collecting and crushing recycled aggregates compared to ordinary aggregates and using construction waste will participate in environment protection and reduce pollution.

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