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Manufacture of Spongy Gravel from Obsidian to Produce Lightweight and Thermal-Insulating Concrete

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Abstract

The present study aims to convert obsidian rocks into spongy gravel for the use in the production of lightweight and heat insulating concrete. The rocks were burned at 960°C to achieve maximum swelling of the samples, then broken into gravel and sand sizes. For comparison purposes, two other types of aggregates were used, namely pumice and basalt. The main physical tests, such as specific gravity, bulk density, porosity, and water absorption were performed. For testing the resistance of samples to alkalinity, KOH and Na OH solutions were used. The results showed that the obsidian sample gave the best specifications, where its specific gravity was 0.33, while the values were 1.1 for pumice and 2.7 for basalt, with the same results being applied to the other physical tests. After forming the concrete cubes of the three types of aggregates with three mixing proportions (1, 1.5, and 3 of cement, sand, gravel, respectively), the most important physical, mechanical, and chemical tests were performed along with their specific ages. The results were distinct, specifically the specific gravity values of the aggregate concrete samples A and B (1.3 and 1.5, respectively, as compared to the basalt sample, which recorded a value of 2.5. As for the thermal conductivity, a distinct value was recorded for the obsidian sample (0.16 W/m.k) as compared to the pumice and basalt samples (2.1 and 1.32 W/m.k, respectively). Perhaps the reason behind this variation is the pores type of the aggregate produced for the obsidian sample, which were of the closed system. This prevents the seeping of water and cement materials into the body of gravel, keeping it at light weight and providing it with high thermal insulation. As for the alkalinity test, there was no evidence of a reaction with the alkali cement in the obsidian and pumice samples, except for a slight reaction that appeared in the basalt sample.

Keywords: Obsidian aggregate, Spongy gravel, Closed pores, Lightweight.

تحويل صخور الاوبسيديان الى حصى اسفنجي لانتاج خرسانة كونكريتية خفيفة الوزن وعازلة للحرارة

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الخلاصة

تهدف الدراسة الحالية الى تحويل صخور الاوبسيديان الى حصى اسفنجي لاستخدامه في انتاج خرسانة كونكريتية خفيفة الوزن وعازلة للحرارة, وذلك من خلال حرق عينات الاوبسيديان وتحديدا بدرجة حرارة (960° م) لتحقيق اعلى انتفاخ للعينات ومن ثم تكسيرها الى احجام الحصى والرمل المطلوبة لاعمال الخرسانة الكونكريتية, ولأغراض المقارنة استخدم نوعين آخرين من الركام هما البيومس والبازلت. اجربت الفحوصات

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الفيزيائية الرئيسية كالوزن النوعي والكثافة الحجمية والمسامية وامتصاص الماء, كما تم استخدام المحاليل (Na OH, KOH) لفحص مقاومة النماذج للقلوية. اظهرت النتائج بان عينة الاوبسيديان A اعطت افضل المواصفات حيث بلغ وزنها النوعي (0.33), في حين سجلت (1.1) للبيومسB و(2.7) للبازلت C, وكذلك الحال لباقي الفحوصات الفيزيائية. وبعد تشكيل المكعبات الخرسانية لأنواع الركام الثلاثة بنسب خلط (1, 1.5 , 3) (اسمنت , رمل , حصى) على التوالي اجريت عليها اهم الفحوصات الفيزيائية والميكانيكية والكيميائية وبإعمارها المحددة, وكانت النتائج متميزة وتحديدا قيم الوزن النوعي لخرسانة الركام نوعي A,B حيث سجلت قيم (1.3) و (1.5), على التوالي مقارنة بالعينة(C) التي سجلت قيمة(2.5) , وبالنسبة للتوصيلية الحرارية فقد سجلت قيمة متميزة للعينة A بمقدار(0.16) مقارنة بالعينتين (C,B) اللتان سجلتا (1.32, 0.21) واط / م. كلفن. ولعل السبب يعود الى نوع مسامات الركام المصنع للعينة (A) والتي كانت من النوع المغلق مما منع تسرب الماء والمواد الاسمنتية الى داخل جسم الحصى وأكسبتها وزنا خفيفا وعزلا حراريا عاليا. اما بالنسبة لفحص القلوية فلم نلحظ اي آثار للتفاعل مع قلويات الاسمنت في العينتين A, B, باستثناء تفاعل طفيف ظهر في العينة C .

Introduction

Due to the great importance of thermal isolation for reducing the consumption of energy used to cool facilities, recent years have seen a great trend for many countries to manufacture of heat-insulating building materials. This particularly includes lightweight concrete, as it represents the most influential aspect of thermal conductivity, as well as being lightweight with less loading on the foundations, thus reducing the use of rebar. Since the weight of rough aggregate (gravel) in concrete represents 70-75% of the weight of concrete [1], it must be replaced by lightweight aggregate. For this reason, an attempt has been made to manufacture spongy aggregates from local Yemeni materials at low economic cost, through the use of widespread and untapped obsidian rocks in other industries. The aim was to process these materials in simple ways and convert them from non-porous rocks with high intensity and specific gravity to lightweight spongy rocks to suit the requirements of the light concrete industry. This process is achieved by burning the obsidian rocks at high temperatures, after breaking them to suitable sizes.

The present study is the first of its kind that deals with the manufacture of spongy gravel into a lightweight aggregate composition used in the production of lightweight thermal-insulting concrete. A previous study reported the production of lightweight concrete using porcelanite rocks [2].

The obsidian rocks are amorphous volcanic igneous rocks that result from the rapid cooling of volcanic lava emanating from the depths on the surface. When they emerge to the surface, the volcanic glass masses are very clear in the upper parts of the lava. Hence, the gradient in the crystals size begins with increasing the depth, where the small crystals appear, and then the largest until reaching the site of rhyolite. This phenomenon explains the presence of obsidian accompanying the rhyolite [3].

The obsidian rocks are characterized by a glassy luster with a concoidal fracture. They have black color tilted to dark brown, despite their silicate acidic composition, perhaps due to the very fine impurities of iron and magnesium minerals. The silica structure is due to the high percentage of silica (> 76%) [4] (Table -1), while the hardness of these rocks ranges 4-5 [5].

The reason for selecting obsidian rocks to produce lightweight aggregate is their ability to release a huge amount of gases during melting as a result of exposure to high temperatures. In order to keep the bubbles inside the body of the obsidian samples, the burning must be stopped at the beginning of the partial melting process. The factor that helps in delaying the escape of gas bubbles is the high viscosity of the molten material. Thus, the volumes of the burned obsidian rocks will multiply to nearly five times with a relatively low density.

Geological Setting

The obsidian rocks are present in large areas of the Republic of Yemen, especially in the areas of Dhamar and Radaa, as well as in Ibb, Taiz, Aden and Marib [6], as shown in the map (Figure-1). This was confirmed by studies carried out by the geological survey and mineral resources during the search for volcanic rocks. This was confirmed by field evidence for many areas during our field visits, where these rocks were seen scattered in different sizes and are often associated with the rhyolite rocks and volcanic eruptions, indicating that extreme volcanic eruptions and explosions were ejected at high altitudes to cover relatively large areas. The presence of obsidian is confined to the volcanoes of

Yemen (Late Tertiary) accompanied by the rocks of the rhyolite and sometimes overlapping or in the form of pockets inside the rocks of the rhyolite. While, in the volcanoes of the Quaternary, there are several detections of obsidian accompanying the rocks of the Rhyolite, volcanic tuff and ash. Here it should be noted that the modelling carried out in the current research was limited to areas near the city of Dhamar, such as the area of Waraqa - Mount al-lisy and the area of Sama – Jawla, as illustrated in the map (Figure-2). The samples of the obsidian were taken from sites located between the village of Waraqa and Mount Elsi 1,606,000 north - 8,450,500 east, 15 km east of Dhamar. The reserves for this sector are estimated at about 30 million cubic meters. The location is also between the Sama area and the Jawla (1,601,000 N. - 8,444,500 E.), 18 km southeast of Dhamar city and 2.5 km south of Dhamar-Radaa road. There is a stratigraphic sequence of volcanic ash and volcanic glass (Obsidian), dating back to the Quaternary, with a thickness of 2-4 m covered by a thin layer of dust (0.4 m). The reserve is estimated at about 4.5 million cubic meters [4].

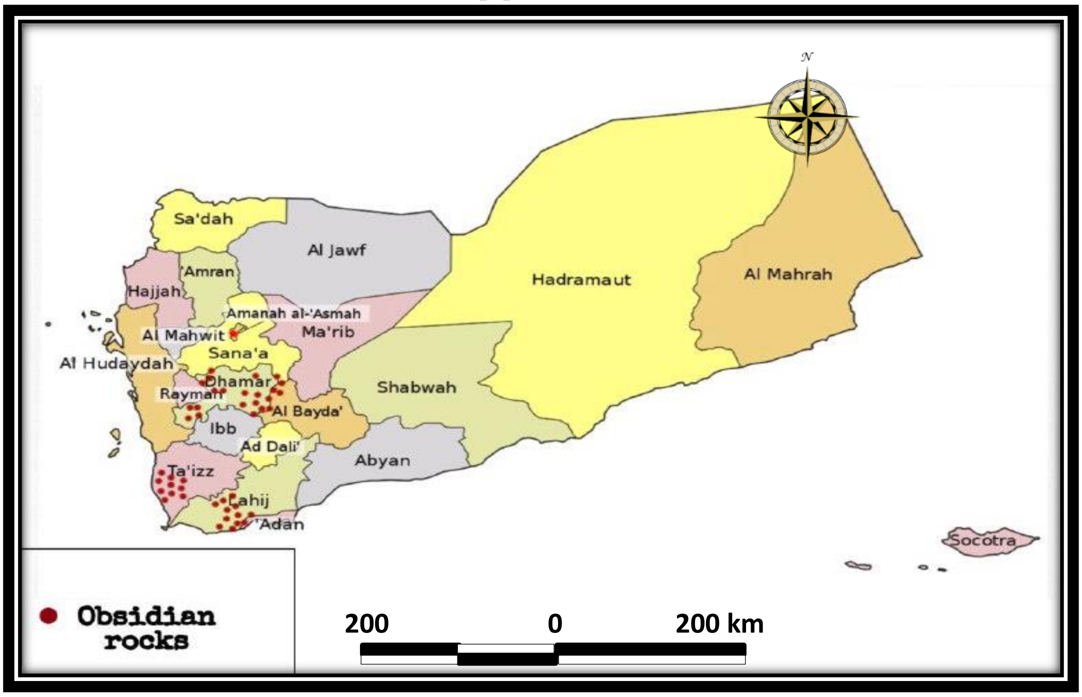


Figure 1- Obsidian rock sites in the Republic of Yemen [4]

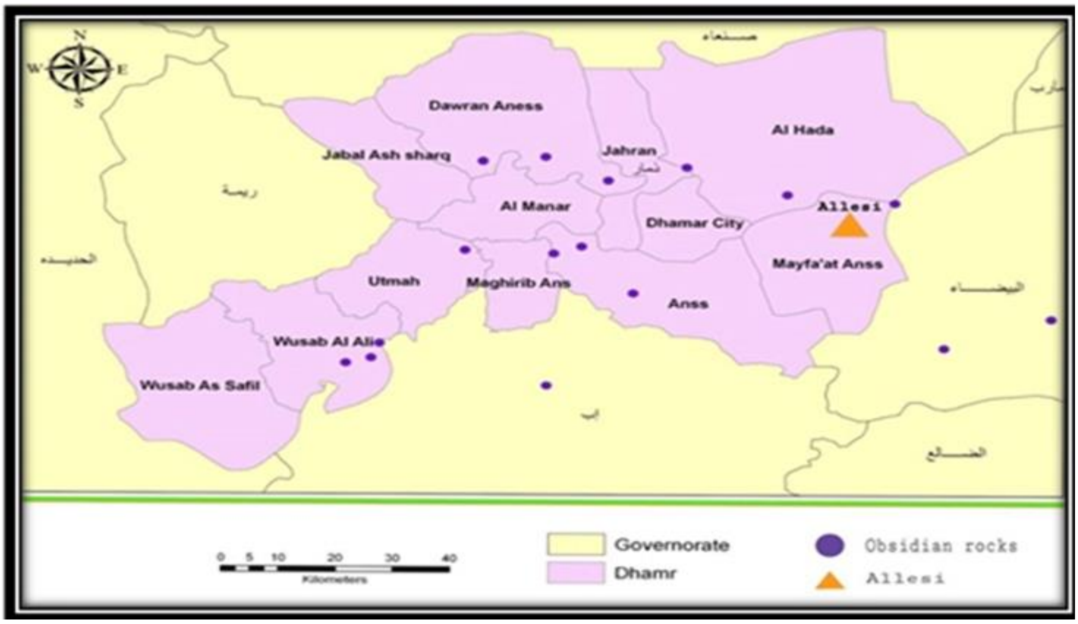
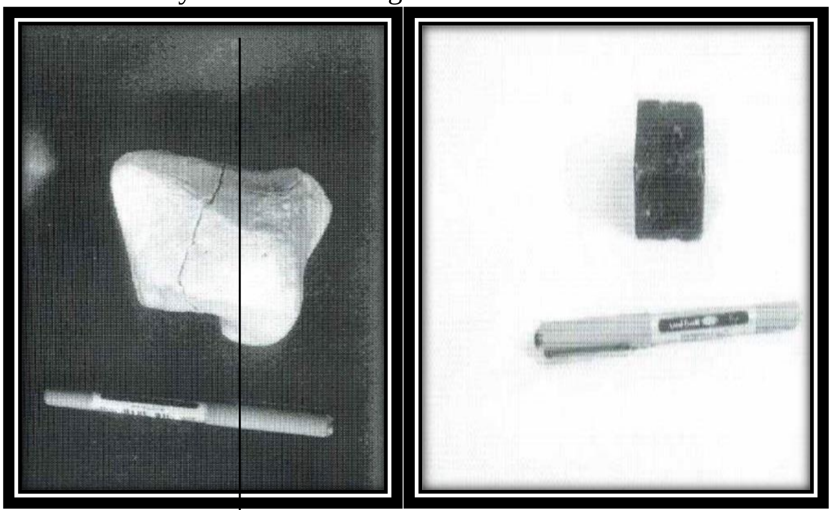


Figure 2- Study sites in Jabal al-Lisy and Jawla, Dhamar Governorate, Yemen Republic [4] (Modified)

Materials and Methods

Manufacturing and Evaluation of Lightweight Aggregates

Obsidian samples were collected from the sites selected in the current study at their natural sizes at the site, which ranged from large pieces of boulders size to smaller pieces of coarse gravel sizes. They were broken in the laboratory of the Department of Geology/University of Dhamar by a usual hammer to soft gravel sizes that fit the size of the burn furnace used in the geological section, which has a width of 20 x 20 cm and a depth of 40 cm. It should be noted here that, before the start of the processes of burning manufacturing of the light aggregate, and for the purpose of experimentation and determining the appropriate burning temperature, some samples were burned individually. The process was repeated several times until the optimal temperature of burning was reached (960°C), in which we were able to achieve the highest swelling of the samples, until reaching the production of spongy gravel. A lower temperature did not achieve a complete bulge of obsidian, whereas a higher temperature causes the model to start partial fusion, leading to a decrease in volume. This temperature is therefore adopted in the current research as the best burning temperature, in which the models have the largest volume and lowest specific gravity. In order to estimate the increase in volume as a result of burning, a model of cubic-shaped obsidian with a length of 3.5 cm (Figure- 1-a) was prepared and burned at the same estimated optimal temperature (960°c). The results showed an increase in the volume of the sample to higher than four times its original size (Figure- 1-b), so that it touched the ceiling of the oven chamber which led to the deformation of its cubic shape. Therefore, after determining the appropriate burning temperature, as well as the ratio of increase in volume, the obsidian models were broken into very small sizes (4-5 mm) and then burned. Here, we emphasize that the burning time must not exceed the time of the final bulge, which means not to keep the models exposed to the final temperature for any longer period. Instead, the oven must be turned off immediately and its door must be opened with a very small opening at the moment the temperature reaches the specified final degree. Otherwise, the models will start the process of partial fusion and then change their qualities. Also, the oven must be left as it is for 42 hours until it cools down, then the models are taken out to be ready for concrete usages.



(B) **(A)**

Figure 3- Obsidian (B- after) (A- before).

For the purpose of evaluating the planted aggregate and testing its suitability as a lightweight aggregate in the production of light and thermal-insulating concrete, several laboratory tests were conducted. These included specific weight, volumetric density, porosity, and water absorption, which are common examinations in the field of evaluation of this type of aggregate [7]. Also, for the purpose of evaluation, the quality of lightweight industrial aggregate (produced in the current research) was compared with that of two types of aggregates, namely the lightweight natural aggregate (pumice) and normal weighted natural aggregate (basalt aggregate) (Table -2). These materials were used because of their worldwide use in previous researches for comparison purposes, in addition to other types of lightweight aggregate such as diatomite, vermiculite, and perlite [8].

Table 2- Results of physical examinations of aggregate models

Sample Type	Water % Absorption	Porosity %	Bulk Density gm. / cm^3	Specific Gravity
Light Weight Aggregate (A) (Obsidian)	9.81	70.88	0.57	0.33
Light Weight Aggregate (B) (Pumice)	36.15	59.33	0.79	1.10
Natural Aggregate (C) (Basalt)	0.20	0.56	2.37	2.75

These tests were carried out in the laboratories of the Department of Geology/ University of Dhamar according to U.S. specifications [7].

Dry weights (W1), saturated weights (W2), and submerged weights (W3), and liquid density (ρ_L) were calculated. These weights were calculated for three samples from each of the three types of aggregates. Then, the average value used in the following equations was adopted.

The specific gravity of the gravel is one of the most important characteristics that determine the suitability of the aggregate to produce lightweight and heat-insulating concrete. To calculate the specific weight of the three samples, (Sample A: spongy gravel manufactured in the current research; Sample B: lightweight pumice; Sample C: normal weight basalt gravel) the following formula was applied:

$$Specific\ Gravity = \left(\frac{W1}{W1 - W3}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

The results are included in Table-1, showing that the lowest value is for sample A (0.33), followed by sample B (1.10), while sample C has a very high value (2.75). According to these results, sample A is most suitable for producing lightweight concrete.

For calculating the bulk density, the following formula was applied:

$$Bulk\ Density\ \left(\frac{gm}{cm^3}\right) = \left(\frac{W1}{W2 - W3}\right) \times \rho L \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (2)$$

The results in Table-1 show that the lowest and, hence the most suitable density was recorded for sample A, followed by sample B, and sample C with a very high density.

For porosity calculation, we used the following formula:

$$Porosity\ \% = \left(\frac{W2 - W1}{W2 - W3}\right) \times 100 \ \ldots\ldots.\ldots\ldots\ldots\ldots\ldots..\ldots\ldots.. (3)$$

The results show that the highest porosity ratio was for sample A, followed by sample B, and then sample C with very little to no pores.

To calculate the ratio of absorption of water, the following equation was used:

$$Water\ Absorption\ \% = \left(\frac{W2 - W1}{W1}\right) \times 100 \ ..\ldots\ldots.\ldots\ldots\ldots\ldots (4)$$

The results showed that the water absorption ration for sample A is much lower than that for sample B, which indicates that the proportion of closed pores in sample A is much higher than that in sample B. Thus, sample A is the most appropriate for the production of light-weight concrete because cement materials and water are not able to access gravel pores.

In other cases, the process of burning the obsidian rocks transformed it from non-porous rocks to spongy rocks with many pores. The reason for the success of this product and its suitability for the production of light and heat-insulating concrete are not because of the many pores it contains but because of their type, which are of closed type. This factor plays a major role, in addition to the change in all physical characteristics of the material. Table-3 shows the differences in the most important physical qualities before and after the burning of the obsidian.

Table 3- Differences in physical properties of obsidian sample before and after burning.

Obsidian	Water Absorption %	Porosity %	Bulk density Gm./cm^3	Specific Gravity
Before burning	Zero	Zero	1.80	1.88
After burning	9.81	70.88	0.57	0.33

The alkalinity test was performed to assess the extent to which the gravel is affected by the alkalinity of cement. This is one of the most damaging chemical reactions to concrete, due to the interaction between cement and silica in the rubble (if it was free silica). This reaction leads to the erosion of the outer edges of the gravel and the appearance of a white gelatinous substance that acts as a buffer between the gravel and concrete bodies. As a result, a weakening of the bonds between the two bodies will occur, which is so-called concrete failure [9].

Accordingly, each of the three types of gravel was tested with the KOH and NaOH alkali by immersing the gravel sample of these two substances in two beakers and placing them in an oven under 50°C. Then, the samples were tested with the naked eye or with a microscope in the ages of 7, 14, and 28 day).

The results showed that, at the age of 28 days, a slight trace of gelatine appeared in sample C, which was only observed using the magnifying lens. However, samples A and B did not have any effects or interactions with the alkaline materials (Figure -4).

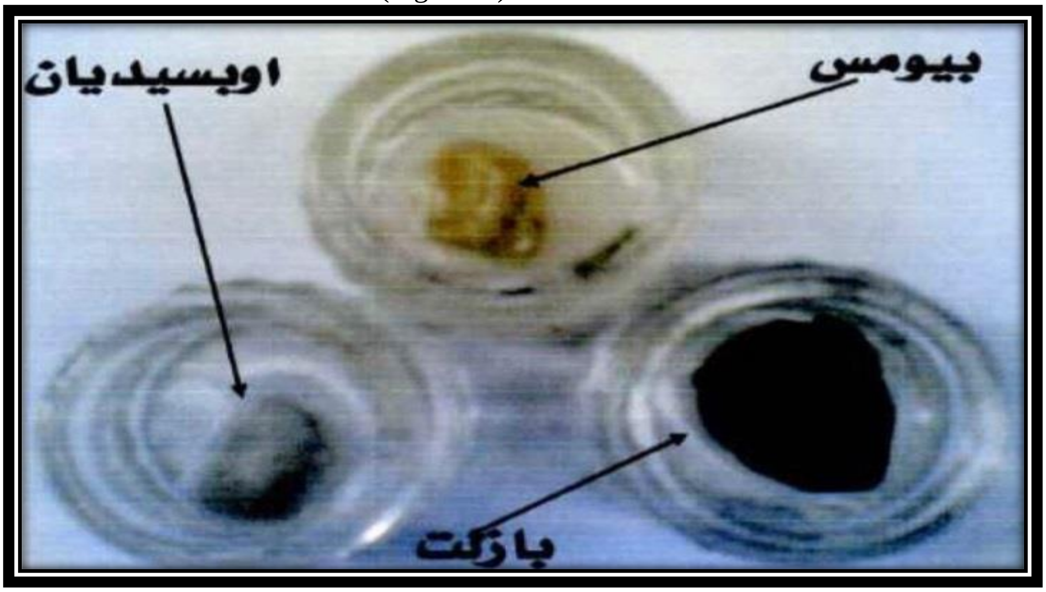


Figure 4- The effects of alkaline substances on the types of aggregate at the age of 28 days.

Manufacture and Evaluation of Lightweight and Thermal Insulating Concrete

The concrete mixture is also known to consist of three main components: cement, sand, and gravel with certain universally agreed proportions, in addition to water .In the current research, these three pre-prepared materials were mixed manually. Since the first-time castor (gravel and sand) of the obsidian was not previously used in concrete, a concrete mixture was designed in new proportions to suit its specifications. In order to compare the specifications of concrete to be produced in the current research, the raw materials were equipped to produce two other types of concrete. The first type was light and insulating concrete, in which the pumice was used as a light coarse aggregate (gravel) and soft (sand). The second type was a regular concrete in which basalt rock was used as a coarse aggregate and silica sand (glass sand) as soft aggregate.

A sufficient quantity of raw materials was prepared and processed through some laboratory operations. These included the process of breaking rock pieces into gravel sizes (8-16 mm) and grinding the remaining to sand sizes (1-2 mm) , according to the U.S. specifications [10] for both gravel and sand of obsidian (Figure -5), gravel and sand of pumice (Figure -6), and basalt gravel and silica sand (Figure -7). To name the samples, the same symbols were used as in the first part of the research. The domestic-made standard national Portland cement was used in all experiments.

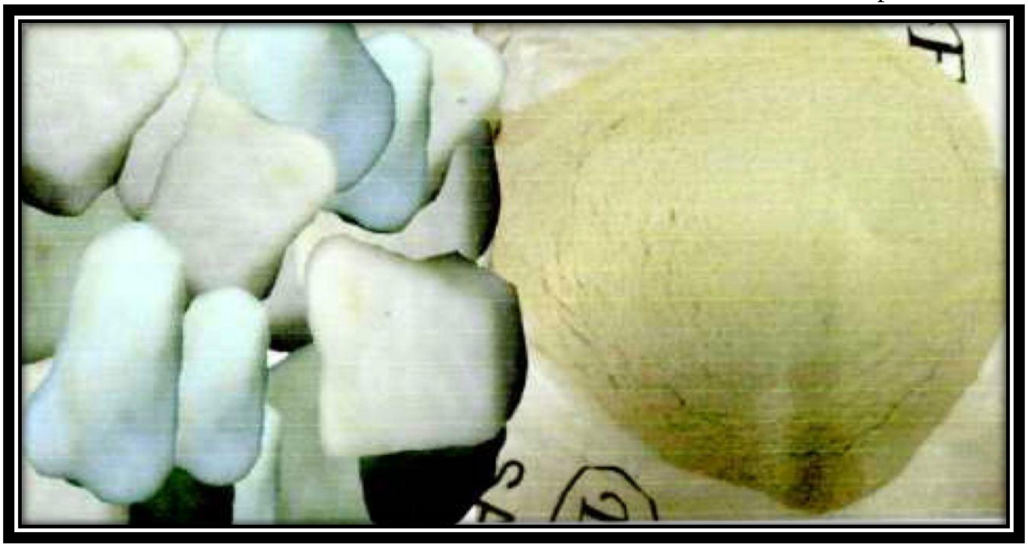


Figure 5- Gravel and sand of the obsidian.

Figure 6- Gravel and sand of the pumice.

Figure 7- Basalt gravel and silica sand

For the purpose of obtaining the best mixing ratios that fit to the new product, several experiments were conducted down to the ratio of 1:1.5:3 (cement: sand: gravel). Determining the ratios of concrete mixture is of great importance [11, 12]. Since this type of aggregate is used for the first time in the current research, these many experiments were conducted to reach that ratio. In order to pour the concrete samples, a cube-shaped iron mold with a rib length of 10 cm (Figure-8) was used, with six models being formed, two of each of the three types of gravel.

24 hours after the concrete was poured, sand was sprayed with water for three days. To keep it moist, all sides were covered with a wet cloth, and which it was flooded with water for a week and then became ready for physical tests, such as specific gravity, bulk density, porosity, and water absorption. However, compressive strength was tested at the ages of (7) days and (28) days, according to the British specification [13]. Also, thermal connectivity was also measured in the concrete samples. Here, it should be noted that physical tests of concrete samples were conducted following the same ways and formulas adopted on the aggregate samples in the previous paragraphs.

Figure 8- Concrete Models

The specific weight test is one of the very important tests, specifically in light concrete where it is considered one of the specific features of the validity of concrete for special construction uses. For the purpose of comparison, the specific weight tests was conducted on the three samples of A, B, and C (Table- 4). The results show that the lowest value for specific weight is 1.3 for sample A (manufactured spongy gravel), which slightly better than that of the natural light gravel B (1.5), while sample C had a value of 2.5. For the bulk density test, he values were 1.1 for sample A, 1.2 for sample B, and 2.3 for sample C. The porosity ratio reached its highest value (16.5 %) in sample B, while a lower value was recorded in sample A (14.4 %) and the lowest was in sample C (7.1 %). These results are due to the type of porous spongy sample A, which has a closed type, while sample B has an open gravel porous type, which allows water and cement materials to enter into the body of the gravel and thus increase its specific weight. . This proves the success of the production of lightweight and heat-insulating concrete. The same applies to the results of the water absorption test; the highest absorption of sample B (13.4), the lower for sample A (12.9), and the very low for sample C (3.1).

Table 4 - Results of physical examinations of concrete models.

Type of Concrete	Water Absorption %	Porosity %	Bulk Density gm./cm^3	Specific Gravity
Obsidian	12.9	14.4	1.1	1.3
Pumice	13.4	16.5	1.2	1.5
Basalt	3.1	7.1	2.3	2.5

The compression resistance of concrete cubes of all three types was also tested and compared, due the importance of this examination in determining the quality and durability of the concrete [14]. The device used for this purpose is the compression resistance test device located in the laboratories of the Faculty of Engineering/ Dhamar University. The results are included in Table- 5, which shows that the highest compression resistance was recorded for the normal-weight natural aggregate concrete sample C (2.6 N/mm2), while the values were 1.7 for sample A and 1.5 for sample B. These results are universally accepted for lightweight concrete specifications, here a non-bearing concrete is used for roofing [15] as well as in the construction monument with distant spaces [16].

Table 5- Results of compression resistance test.

Compression N/mm^2	Type of Concrete
1.7	Obsidian
1.5	Pumice
2.6	Basalt

For the purpose of thermal conductivity test, a heat - emitting source and a receiver were used, and a concrete cube was placed between them. The thermal conductivity of the concrete cube was calculate through the difference between the value of the heat emitted and the heat received through the sample, taking into account the thickness of the tested sample. The three types of concrete samples were tested. The results of the test (Table -6) showed a remarkable distinction of aggregate concrete sample (A) compared to samples (B & C).

Generally, the obsidian concrete is characterized by its lightweight and thermal insulation, as it characterized by the lack of cracks, gaps, and channels, which can be distinguished by ground penetrating radar [17].

Finally, the manufacture of lightweight concrete from obsidian is characterized by the absence of associated source of environmental pollution, unlike the production of some other building materials such as bricks, which is accompanied by the emission of high amounts of gases and suspended particles with different concentrations of heavy elements [18].

Table 6- Thermal conduction test results for concrete models.

Thermal Conductivity W/mk	Type of Concrete	Sample
0.16	Obsidian	A
0.21	Pumice	B
1.32	Basalt	C

Conclusions

The results obtained from the process of manufacturing and evaluating spongy gravel, from which lightweight and thermal insulating concrete was produced, demonstrated that the rocks of the obsidian, upon burning and reaching the stage of the beginning of suppleness and before total fusion, release a large amount of gases. However, the high viscosity of the diluted material prevents the escape of gases which remain in the form of bubbles. This works to bulge the rock to several times larger than its original size. This occurs at a temperature of 960°c, at which the solid obsidian rocks turn into a liquescent material. This material has a viscosity degree capable of holding the released gases in the form of bubbles of huge numbers, leading to the rock bulge. However, when the temperature is raised more, the viscosity will decrease and therefore the gases escape and the rock begins to shrink. We also conclude that these bubbles are of the type of closed pores, based on the results of high porosity and low water absorption of the aggregate produced. This characteristic was the reason for the success of this type of gravel in the production of lightweight concrete, because of the inability of water and materials of the cement to enter the body of the gravel. This characteristic even outweighs that in the gravel of the pumice which has the highest ratio of open pores.

This property also provided the high thermal insulation of this type of concrete, certainly due to the presence of a large percentage of air inside the bubbles.

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