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Constructing a Sustainable Roller Compacted Concrete Using Waste Demolished Material as Replacement of Cement: A Review

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ABSTRACT

Roller Compacted Concrete is a type of concrete that is environmentally friendly and more economical than traditional concrete. Roller Compacted Concrete is typically used for heavy-duty and specialist constructions, such as hydraulic structures and pavements, because of its coarse surface. The main difference between RCC and conventional concrete mixtures is that RCC has a more significant proportion of fine aggregates that allow compaction and tight packing. In recent years, it has been estimated that several million tons of waste demolished material (WDM) produced each year are directed to landfills worldwide without being recycled for disposal. This review aimed to study the literature about creating a Roller-Compacted Concrete (RCC) mix with modified engineering properties with favorable environmental impact, so it was focused on investigating using different proportions of waste (Glass, Brick, and Marble), which are the most waste-demolished materials (WDM) widely in the world, as a partial substitute of cement. Then, study the influence on the durability and mechanical strength of (RCC) produced with and without these waste powders.

Keywords: Waste Demolished Material (WDM), Roller-Compacted Concrete (RCC), Waste Bricks Powder (WBP), Waste Glass Powder (WGP), Waste Marble Powder (WMP).

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انتاج الخرسانة المستدامة المرصوصة بالحدل باستخدام نفايات مواد البناء المهدمة كبديل : مراجعة للأسمنت

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الخلاصة

الخرسانة المرصوصة بالحدل هي نوع من أنواع الخرسانة الصديقة للبيئة، والتي تعتبر أكثر اقتصادية من الخرسانة التقليدية. عادةً ما يتم استخدام الخرسانة المرصوصة بالحدل للمنشأت الثقيلة و المتخصصة، كالهياكل الهيدروليكية والارصفة نظرًا لسطحها الخشن نسبيًا. يتمثل الاختلاف الرئيسي بين خلطة الخرسانة التقليدية وخلطة الخرسانة المرصوصة بالحدل في أن نسبة الخرسانة المرصوصة بالحدل بها نسبة أكبر من الركام الناعم الذي يسمح بالضغط والتعبئة المحكمة. في السنوات الأخيرة، ملايين الاطنان من النفايات للمواد المهدمة حول العالم سنويا يتم توجيهها إلى مكبات النفايات، بدون أي اعادة لتدويرها للتخلص منها. يهدف هذا البحث لمراجعة الدراسات حول انتاج خليط الخرسانة المرصوصة بالحدل بكلف قليلة مع تعديل الخصائص الهندسية بشكل يناسب البيئة، لذلك، ركز البحث على دراسة استخدام نسب مختلفة من مخلفات (الزجاج، الطابوق، والمرمر) التي هي من أكثر نفايات البناء المهدم انتشارا بالعالم، كاستبدال جزئي للاسمنت، لدراسة تأثيرها على القوة الميكانيكية والمتانة للخلطات بدون او مع مساحيقها.

الكلمات المفتاحية: نفايات المواد المهدمة، الخرسانة المرصوصة بالحدل، مطحون الزجاج.

1. INTRODUCTION

Roller-compacted concrete was first produced in North America as an airfield runway constructed in 1940 in Yakima, D.C. **(Harrington, 2010)**. The term (RCC) refers to concrete compacted by a weighty vibratory steel drum and rubber-tired rollers **(ACI 327, 2015)**. The steps of the paving mechanism in RCC are the same as asphalt paving; individual types of concrete are laid adjacent to each other **(ACI PRC-309.5, 2022)**. The production of (RCC) is generally inexpensive as compared to traditional concrete because the mix (RCC) mix contains less water and cementitious materials 12 %, while (PCC) includes 15 % **(Abbas, 2022)**. A lower quantity of water in the (RCC) mixture limited the shrinkage and bleeding of water. It reduces thermals that cause cracking when using a lower quantity of cement **(Salih and Abed, 2016)**. Moreover, manufacturing cement is more costly and causes environmental pollution. Therefore, this paper discusses the research on the production of RCC mixture using waste demolished material (WDM) since the output of one ton of Portland cement clinker is associated with the emissions of approximately 850 kg of CO_2 **(Puertas et al., 2008)**. Waste-demolished material (WDM) with a high-fineness mechanical property improves durability **(Abbas et al., 2022)**. Therefore, waste materials are milled down to micro-sized particles and used as a component substituting cement. Consider an important point to develop sustainable (RCC) concrete. Waste glass powder (WGP) is a commonly recycled material used to reduce the amount of cement in the (RCC) mixture. According to the chemical composition analysis of (WGP), the main component is silica (SiO_2 > 70 %); the chemical composition analysis of (WGP) is presented in **Table 2**. Hence concrete mixture containing (WGP) gave preferable strength compared with the control mortar **(Islam et al., 2017)**. Moreover, the chemical components included in (WGP) are approximately the same as those in cement **(Hussain and Aljalawi, 2022).** In addition to the (WGP), the recycled material utilized in this research is (WBP). Several researchers investigated utilizing this waste powder as a partial substitution for Cement and assured the possible use of it to produce pozzolanic cement **(Naceri and Hamina, 2009)**. The chemical composition analysis of (WBP) is presented in **Table 3**., and also, (WMP) is used to reduce the quantity of cement in the (RCC) mix. Using recycled waste demolished concrete material in concrete is a useful solution regarding economic, social, and environmental views. By deliberating those three aspects, the usage of (glass, Bricks, and Marble) in concrete is part of the perspective of sustainable development see **Fig. 1.**

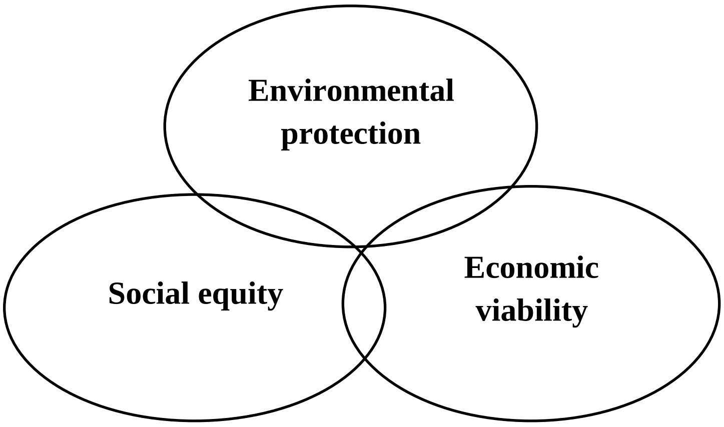

Figure 1. Three spheres of sustainable development.

The general objective of the review is to develop alternative cementitious additions derived from industrial by-products and contribute to helping reduce greenhouse gas emissions. More specifically, the project focuses on incorporating recycled fine materials of waste glass powder (WGP), waste bricks powder (WBP), and waste marble powder (WMP) into roller-compacted and dry-setting concrete.

2. BENEFITS OF UTILIZING RECYCLED MATERIALS IN CONCRETE

The utilization of recycled materials in the manufacture of concrete contains several advantages providing under different aspects **(Shi and Zheng, 2007)**:

- Reduces waste disposal costs that must increase due to landfill taxes.
- Protect the environment by saving large quantities of raw materials.
- Extend the useful life of landfills and help protect the countryside.
- Significantly reduces energy consumption (CO_2), (NOx), and other emissions of air pollutants caused by cement manufacturing when used as a cement substitute in concrete.
- Growth of common knowledge on waste issues and the advantages of reused materials.
- Presentation alternatives for using recycled products (glass, brick, and marble) without compromising cost or quality.

3. ROLLER-COMPACTED CONCRETE

Just like its use and installation techniques, the formulation of (RCC) differs from that of usual concretes. Based on a granular skeleton with maximum compactness and an optimal paste volume, it is possible to produce (RCC) for paving with mechanical properties superior to conventional concrete **(Vahedifard et al., 2010)**. Roller-compacted concrete has the advantage of being unreinforced, economical, quick, and easy to place, and it requires little or usually no formwork. There are two main categories of (RCC) for paving and dams. Dams (RCC) are used for the construction of cores of dams or dykes. (RCC) paving is used in places with slow traffic: parking lots, storage, recycling or composting areas, etc. Base Course Reduction (BCR) for paving is adequate for sites with heavy machinery traffic. (RCC) offers a quality surface finish and, unlike asphalt, excellent rut resistance. Roller-compacted concrete is usually made in a pug mill-type mixer that can produce a homogeneous mixture within specified tolerances. It provides enough mixing power to evenly disperse the small water throughout the concrete mix. The production plant has the advantage of being mobile, shortening transport distances between the plant and the site. The concrete is transported to the placement site using conventional dump trucks. The concrete is then placed using pavers for the placement of bituminous mixes. Minor modifications may be required to the device to accommodate thicker layers and more significant amounts of material. (RCC) usually placed in lifts of (150 to 200 mm) with a 100 mm minimum and 250 mm maximum **(ACI PRC-309.5, 2022)**. After being placed by the paver, the concrete is consolidated using roller compactors to obtain maximum compactness (reduction of voids) and a uniform surface finish. Placing the (RCC) using conventional paver and roller compactors is shown in **Fig 2.** Given no bleed water in roller-compacted concretes and evaporation occurs immediately, which may result in surface deterioration through shrinkage cracking and shallow micro-cracks, proper curing is essential immediately after placement to prevent excessive evaporation from the pavement surface after final compaction. Various curing techniques, such as membranes, canvases, cotton mattresses, wet sand, sprinkler trucks, etc. **(American Concrete Institute, 1987)**.

Figure 2. Setting up the RCC **(Harrington et al., 2010)**.

4. WASTE-DEMOLISHED GLASS (WDG)

4.1. Recycling of Waste Glass

Each year around the world, one million tons of Waste Glass are created. When the glass turns into waste, it's far from being disposed of in unsustainable places because it no longer decomposes within the atmosphere **(Islam et al., 2017)**. The chemical composition generally depends on the raw material used; it is partly different for each type of glass. The common ($CaHNaO_2$) glasses encompass 70 % amorphous SiO_2, 13 % Na_2O, and 10 % Cao. Glass may be an excellent pozzolanic fabric for the concrete area, being amorphous and owning reasonably massive quantities of silicone. So, (WGP) may be utilized in principle as a partial cement replacement **(Vaitkevičius et al., 2014)**. Research at Columbia University showed that varied colors of glass influence the expansion of concrete **(Meyer and Baxter, 1997; Jain and Baxter, 2010)**.

In contrast, research at the University of Sheffield showed that there wasn't any variance in the varied colors of glass **(Zhu and Byars, 2004)**. In many countries, glass may be reused after consumption without significant adjustments in its physical and chemical properties. Environmental problems occur due to the sedimentation of (WGP) in deposits of its non-biodegradable nature. Due to the lower rate of treatment, waste glass is a global problem with solid waste control systems. (WGP) It can be used in varieties of concrete, e.g. (RCC) as a partial replacement for cement as it is a hard fabric with nearly negligible water absorption. Moreover, the chemical composition and the physical properties of (WGP) are identical to those of sand and concrete. Grounding the (WGP) in a fine powder is an important solution for the environmental impact. Worldwide recycling rates are low and usually concentrate on the container and packaging sector. **Table 1** presents the quantity of (WGP) and the recycling rate in various countries.

Table 1. The quantities of waste glass and the recycling rate in various countries **(Jani and Hogland, 2014).**

NO.	Country	Glass waste tons	Percentage of the recycling rate %	Year
1	USA	11,500,000	27	2010
2	Germany	3,200,000	94	2003
3	Portugal	493,000	25	2001
4	Sweden	195,000	93	2010
5	Turkey	120,000	66	2004
6	Canada	116,000	68	2009
7	Singapore	72,000	29	2010
8	Jordan	35 building glass	0	2004

4.2. Waste Glass Powder

Waste glass powder (WGP) is obtained from grinding crushed, mixed glass and consists mainly of amorphous silica. **Fig. 3** illustrates the Microstructure of waste glass powder (WGP). **Table 2** shows the chemical characterization of (WGP).

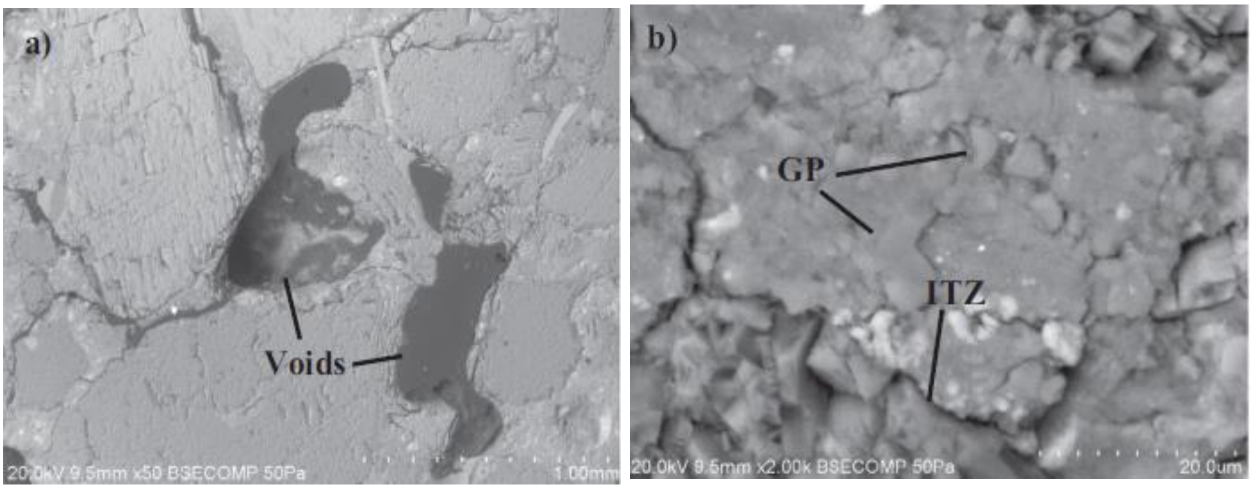

Figure 3. SEM micrographs of Int.GP RCC slabs: **a)** sub-millimeter scale disconnected voids, **b)** GP particles bonded by dense C-S-H. **(Omran et al., 2017).**

Table 2. Chemical compositions of (WGP) **(Du and Tan, 2014)**.

Composition %	Glass powder
SiO_2	72.08
Al_2O_3	2.19
Fe_2O_3	0.22
CaO	10.45
MgO	0.72
Na_2O	13.71
K_2O	0.16
TiO_2	0.1
Cr_2O_3	0.01
SO_3	-

Glass powder consists mainly of vitreous silica. This vitreous state is obtained during the rapid cooling of the silica sand during the glass manufacturing process. The absence of a clear peak indicates the absence of an element crystalline in the composition of the material **(Shi and Zheng, 2007).**

4.3. Pozzolanic Activity of Glass Powder

The hydration reaction of Portland cement is special because of the reaction of silicate tricalcium (C_3S) with water (H_2O)., and results in hydrated calcium silicate (C-S-H) and portlandite (CH). This reaction is rapid and produces extensive temperature emissions. The hydration reaction can be summarized this way **(Saluja and Bhattacharjee, 2019)**:

$$\mathbf{C_3S + H_2O \longrightarrow C\text{-}S\text{-}H + CH}$$

The pozzolanic reaction is a slow process that produces (C-S-H) gels of higher density than those produced by cement hydration. These gels are formed by pozzolans, which consume the lime produced during the hydration of the cement. This reaction can be summarized as follows **(Saluja and Bhattacharjee, 2019)**

$$\textbf{pozzolan + CH} \longrightarrow \textbf{C-S-H}$$

The pozzolanic reaction is characterized by three main characteristics **(Tagnit-Hamou, 1995)**:

- The reaction is slow, as is the evolution of heat and the development of resistors.
- Unlike the hydration reaction of Portland cement, the pozzolanic reaction improves the resistance of concrete in an acidic environment lower (pH) and expends lime.
- Hydration products fill in hair pores and increase resistance and the impermeability of concrete by refining the capillary pores and transforming large (CH) crystals into a weakly crystallized hydration product (grain refinement).

  Several factors influence the pozzolanic effect of glass powder: the chemical composition of the glass, the grain size, the chemical composition of the cement, the presence of other additions, temperature, type of cure, particle shape, etc.

4.4. Particle Size and the Pozzolanic Reaction of Glass Powder

Various studies show that the particle size of the glass powder influences its pozzolanic effectiveness **(Idir et al., 2010).** In their work **(Shao et al., 2000),** they used three glass powders different in particles to produce concrete. The first powder consists of particles with a diameter of 150 to 75 µm, the second from 75 to 38 µm, and the particles of the third powder have a diameter of less than 38 µm. These powders are named respectively 150 µm, 75 µm, and 38 µm. Due to its larger particle size, the 150 µm powder does not meet the requirements of ASTM C618 standard to qualify as a pozzolan. The 75 µm powder showed marginal results depending on the percentage of particles that passed the 45 µm sieve. Therefore, only a 38 µm powder has sufficient fineness to exhibit pozzolanic behavior. By replacing 30 % of the cement with additive minerals in concrete, it has been observed that mixing with 38 µm glass powder exceeded the compressive strength of the fly ash mix at 3, 7, 28, and 90 days. Therefore, the glass powder's diameter is directly related to the pozzolanic efficiency of glass powder.

4.5. Curing Temperature

The increase in temperature during the curing accelerates pozzolanic activity for (WGP) **(Shi et al., 2005)**. It was observed that by increasing the curing temperature from 25°C to 35 and 65°C, the pozzolanic activity grew from 1 to 28 days. As the curing temperature rises from 23 to 65°C, the 7-day compressive strength of concrete decreases from 29 to 24 MPa, while in a mixture containing 20 % (WGP), it increases from 27 to 30 MPa., and in 28 days, the decrease is 35 to 26 MPa, while in the mixture with (WGP), it decreases from 38 to 34 MPa.

4.6. Alkali-Silica Reaction

The alkali-silica reaction (RAS) is the most frequent in concrete. Three conditions must be met simultaneously to allow the alkali-aggregate reaction: the aggregates must be potentially reactive, the concentration of alkalis in the interstitial solution of the concrete must be high enough, and the concrete must be wet. The alkali-silica reaction produces expansive gels that can crack concrete, cause significant damage to structures, and play an essential role in compressive strength development. The fineness of the (WGP) seems to be a determining factor in controlling the alkali-silica reaction. It is concluded that using (WGP) with a diameter of less than 1 mm decreases the growth resulting from the alkali-silica reaction. In addition, fine glass powders, with a specific surface area between 180 and 540 m^2/kg, reduce the expansion of mortars subjected to an alkali-silica reaction (especially when using vitreous aggregates with a diameter of more than 1 mm) **(Idir et al., 2010). (Shi et al., 2005)** measured expansion for mortar according to the ASTM 311- 07 specification contains 20 % slightly coarser than Portland cement. The expansion of the mortar specimen measured up to 21 days remains lower than that of the reference mixture without (WGP). Similar results were also obtained by **(Shao et al., 2000)**. With a cement replacement rate of 30 %, test specimens of mortar containing (WGP) with a max diameter of 150 and 75 μm exhibited expansions similar to the reference mixture without (WGP). The use of 30 % (WGP) with a maximum diameter of 38 μm made it possible to halve the expansion of mortar specimens with reactive aggregates. Utilizing a (WGP) of sufficient fineness makes it possible to reduce the expansions caused by the (RAS). Work has shown that dry concrete has better (RAS) performance than ordinary concrete (wet mixed) **(Lee et al., 2011)**.

4.7. Penetration of Chlorine Ions

The accelerated chlorine ion penetration test depends on **(ASTM C 1202., 1997)** specification that measures the charge that an electric current passes through a sample of saturated concrete. The first side of the sample is in contact with a solution of (NaCl) while the second is with a solution of (NaOH). The total charge measured over 6 hours indicates the conductivity of the cement and is used as an indicator of the penetrability of chlorine ions inside the cement. Various studies have demonstrated the possibility of (WGP) decreasing the penetration of chloride ions inside the cement **(Shayan et al., 2006; Wang et al., 2009; Jain et al., 2010)**.

5. WASTE-DEMOLISHED BRICKS (WDB)

5.1. Recycling of Waste Bricks

There is a broad range of construction made with clay brick worldwide. The demolition of structures and earthquakes led to the accumulation of brick waste. This destroyed waste has recently been reused as a powder in mortar to reduce its harmful effects and give it suitable properties.

5.2. Bricks powder

Brick Waste is used in powder form in different countries. In Hong Kong, demolished bricks are usually crushed to form fillers; in Japan, they are burned into a slurry that is reduced to ash **(Tam and Tam, 2006)**. The Italians evaluated the opportunity of utilizing (WBP) instead of Portland cement as a cementitious material and found that the mortars containing (WBP) showed suitable performance **(Corinaldesi et al., 2002).** According to research **(Abbas and Abbood, 2021),** the experimental results of replacing cement with nano brick powder showed better mechanical properties (compressive, flexural, and tensile strength) at all ages. The chemical characterization of (WBP) is shown in **Table 3**. SEM morphology of recycled (WBP) is shown in **Fig. 4.**

Table 3. Properties of (WBP) **(Abbas and Abbood, 2021)**.

Tests		Brick Powder
Chemical test - oxides (%)	SiO_2	68.8
	$Al2O_3$	8.4
	Fe_2O_3	2.65
	Cao	7.5
	MgO	4.2
	SO_3	1.56
	L.O. I	2.82
Physical test	Strength activity index	80
	Percentage retained of wet sieved on 45 µm (max.)	0

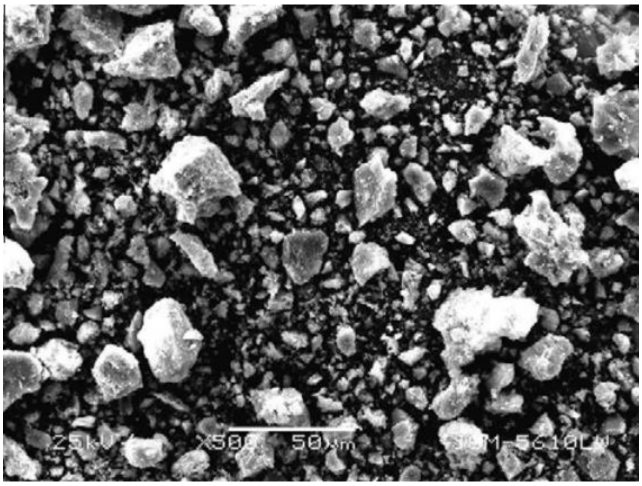

Figure 4. SEM morphology of (WBP) **(Chen et al., 2011)**.

5.3. Pozzolanic Activity of Bricks Powder

The standard used for cement substitutes is the presence of pozzolan, brick powder classified as a pozzolanic material with a content of (SiO_2 +Al_2O_3+ Fe_2O_3) greater than 70 % so that it can be used as a cement replacement, reach to 10 % of cement **(Abbas and Abd, 2021).** Calcium hydroxide created through the hydration of silicates in cement reacts with the effective silica in the (WBP). Then it produces cementitious materials that improve the microstructure of cement paste **(Abbas and Abbood, 2021).**

5.4. Particle Size and The Pozzolanic Reaction of Bricks Powder

The pozzolanic activity and properties of the mixed cement are affected by particle size (WBP). A study **(Zheng et al., 2011)** was carried out on the mortar with clay brick powder grouped into four particle sizes (40 mm, 60 mm, 100 mm, and 300 mm), and observed that the specimen with 60 mm had better strength in comparison with other different specimens. Moreover, improved compressive strength, which grows later, and denser microstructure caused by consuming a smaller particle size of (WBP) more calcium hydroxide to react **(Zhao et al., 2020).**

6. WASTE DEMOLISHED MARBLE (WDM)

6.1. Recycling of Waste Marble

In recent years, marble manufacturing and use in buildings has increased, thus resulting in pollution in nature, which is caused by the cumulation of waste marble. In addition, due to the high chemical content of marble slag, it unfavorable affects the environment, Such as groundwater pollution and low soil productivity. Some researchers suggest a new technique based on addition (WMP) to substitute cement paste without changing its mix proportion, which can reduce the cement content by up to 33 % with improve the carbonation and water resistance, reducing the shrinkage strain and rate. This technique is called the "paste replacement method" **(Li et al., 2018)**. A study found that concrete consisting of (WMP) is 15 % cheaper as compared with traditional concrete **(Uysal and Yilmaz, 2011)**; moreover, the utilization of (WMP) in mix produced 12 % lower CO_2.

6.2. Marble Powder

(Baboo et al., 2011) tested several specimens to substitute varying (WMP) ratios with cement, which resulted in the rise in strength of the mortar and concrete. The chemical characterization of the (WMP) is given in **Table 4.** SEM morphology of (WMP) is shown in **Fig. 5**.

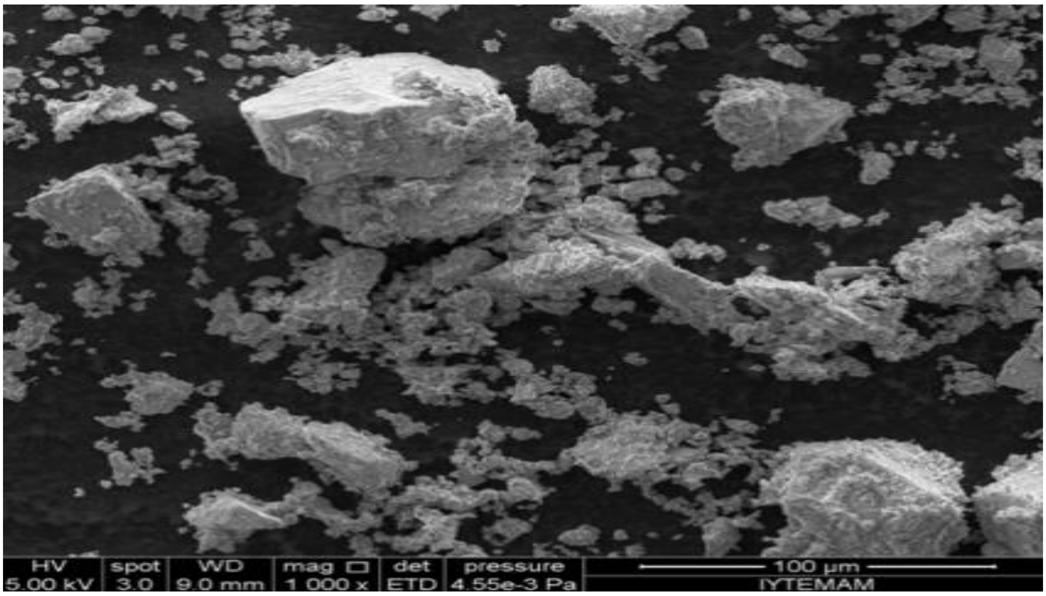

Figure 5. SEM morphology of (WMP) **(Sutcu et al., 2015).**

6.3. Pozzolanic Activity of Marble Powder

As mentioned, a powder is considered pozzolanic material when the sum of (SiO_2+Fe_2O_3+Al_2O_3) is greater than 70 % according to the ASTM C618-12a specification for pozzolanic, which requires. The increased fineness of the (WMP) compared to the Portland cement resulted in an increased pozzolanic activity index **(Patel and Shah, 2015).** The chemical analysis of the (WMP) is presented in **Table 4.** It is observed that the sum of SiO_2, Al_2O_3, and Fe_2O_3 is 76.9 %. Thus, (WMP) is proper to manufacture high-performance concrete by substituting it with cement.

Table 4. Properties of (WMP) **(Patel and Shah, 2015).**

Tests	Marble Powder
Fe_2O_3+Al_2O_3+SiO_2	76.9
SiO_3	1.2
MgO	1.7
Cao	0.32
K2O	0.05
L.O. I	2.9

6.4. Particle size and the pozzolanic reaction of marble powder

(Patel and Shah, 2015) reported that the pozzolanic activity is most favorable for particles with a size of 75 microns or smaller. Due to the increased fineness of the waste powder as compared to Portland cement, the pozzolanic activity index rose. It is important to note that the ASTM specification for pozzolana specifies a sum of (Fe_2O_3, Al_2O_3, and SiO_2) at least 70 %. Additionally, it requires SO_3 to be less than 5 %, moisture content to be under 3 %, and loss on ignition to be under 6 %. These requirements are met by industrial waste powder. Thus, the strength activity index is acceptable. Also, the same researchers observed that when marble powder increased, there were more crystalline particles. Additionally, diluting impact is caused by decreasing $Ca(OH)_2$ and raising powders. Small, unreacted powder particles filled most of the voids, making it behave as an inert filler. As a result of the waste powders consuming $Ca(OH)_2$ through the pozzolanic reaction, strength increased as curing time proceeded.

7. CONCLUSIONS

The utilization of waste-demolished materials as a replacement for cement in roller-compacted concrete is investigated in this review. The following conclusions may be reached based on the preceding:

- The environmental and financial advantages of reusing waste materials as a replacement for cement in (RCC) mixture also can be so large depending on the last utilizes.
- Glass and brick powders show excellent pozzolanic reactivity, thus possibly being utilized as a cement substitute.
- Several factors influence the pozzolanic effect of the waste powder: the chemical composition, the grain size, the chemical composition of the cement, the presence of other additions, temperature, type of cure, particle shape, etc.

- The effectiveness of the (WGP) in increasing the discontinuity of the capillary pores and blocking the migration of chlorine ions in the concrete.
- The beneficial effect of (WGP) is particularly marked when the concrete is stored in conditions of high ambient humidity.
- It has been noticed that the compressive strength of mixtures rises depending on the fineness of the waste powder.
- An alteration by cement weight with (WBP) of up to 10 % achieves good properties in concrete.
- An alteration by cement weight with (WMP) to 10 % achieves high strength.

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