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Mechanical Properties of Ceramic Waste as an Alternative Material of Concrete Aggregate

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Abstract*: *The increasing building construction in the field of civil engineering that requires supporting materials, starting in terms of human resources and material resources. Progress in the material field must consider energy-saving aspects. Therefore it is necessary to think about the use of useless materials such as ceramic waste. The purpose of this study is to see the potential of ceramic waste as an aggregate in terms of mechanical properties, with the hope of providing an alternative to concrete aggregates other than natural stone aggregates. Ceramic waste aggregate material testing is done by testing: chemical composition, absorption and water content, specific gravity, soundness, abrasion, granular form, gradation, and X-ray diffraction (X-RD). The test results show that the ceramic waste aggregate (CWA) can be used as a concrete aggregate. Ceramic waste aggregate (CWA) characteristics are sufficient to meet the standards as concrete aggregates according to the SII standard, BSI standard, and ASTM standards. While the X-ray diffraction test (X-RD) shows that no element damages concrete, there is no active silica that can react with alkaline cement and is not as a pozzolan.

Keywords*: *Mechanical properties, ceramic waste aggregate* (CWA), *ceramic concrete.

I. INTRODUCTION

The increasing development and construction materials industry has an impact on reducing natural resources and environmental pollution. Some important factors that must be considered during building construction such as the level of waste of raw materials and the impact of disposal, renovation, and replacement of building components and their maintenance, and waste treatment during the demolition of the building [1] In the context of promoting sustainable development, the recommended general strategy is to reduce, reuse, and recycle in accordance with aspects of community growth and needs. Waste management and studying the mechanical properties of these waste materials is very important to determine their utilization. Waste recycling is one way to prevent waste materials from entering landfills and reduce supplies sourced from natural resources [2].

Concrete is the main element in the world of construction buildings that continue to dominate until now. Steel is the main material of reinforced concrete derived from fossils that are not renewable and is increasingly depleting its raw material. Concrete aggregate is a concrete material sourced from natural resources and often causes environmental damage due to continuous use. To reduce the depletion of materials originating from natural resources, alternative sources of renewable, energy-efficient, renewable materials must be used, and even the use of waste materials such as ceramic waste. Ceramic waste is a waste that is generated from many sources, including the construction industry waste, building construction waste, and household waste. Ceramic waste is a hazardous waste and causes environmental pollution. Research on the impact of ceramic waste on environmental pollution has been widely carried out, including [3] and [4]. Many opportunities to be researched about reinforced concrete materials including reinforcing materials, cement, fine aggregate, and coarse aggregate. The use of concrete reinforcement material from renewable energy has been widely carried out such as bamboo as a substitute for steel reinforcement for simple construction [5], [6], [7], [21] as well as the use of ceramic waste as concrete material [8], [9], [10], and [22].

Ceramic waste aggregate as a substitute for normal aggregate has been done by Anderson (2016) [2] with the conclusion that the effect of mechanical behavior due to replacement of coarse aggregate varies more than normal concrete, and depends on the mechanical properties of the ceramic waste material used. It is important to understand the influence of the characteristics of different constituent materials on concrete mechanical behavior. Wadie (2017) [11] concluded that recycled ceramic tile aggregates can be used as structural concrete aggregates. Siddique (2019) [12] concluded that concrete with fine bone china ceramic waste aggregate produced concrete that was resilient and durable. Replacement of normal fine aggregate with porcelain ceramic waste aggregate is recommended up to 40% in concrete.

Nepomuceno (2018) [13] evaluates the performance of concrete mechanic using recycled ceramic coarse aggregates from industrial brick waste. The results of his research indicate the feasibility of partial replacement of normal aggregates with aggregates from ceramic waste, although concrete mechanical performance decreases with the increasing replacement of normal aggregates with ceramic waste aggregates. The decreasing performance of concrete [13] indicates a difference in the quality of ceramic waste to the results of other studies that show improved performance. Alireza (2019) [14] concluded that the partial replacement of 40% normal aggregate with ceramic waste aggregate produced optimal mechanical properties and increased compressive strength, tensile strength, and flexural strength by 13%, 15%, and 3%, above normal concrete.

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Muhtar (2019) [15] conducted research on partial replacement of normal aggregate with ceramic waste aggregate showing an optimum value of 55%.

II. MATERIAL AND METHODS

A. Ceramic Waste

The ceramic waste consists of floor ceramic waste, closet, roster, gallon jars, decorative ceramics, and others. ceramic waste is taken from factory waste, household waste, and building waste. The hardness and thickness of ceramic waste vary. The thickness of the ceramic waste is between 5 mm to 10 mm. Then the ceramic waste is milled to a maximum size of 5 mm for fine aggregate, and a maximum of 10 mm for coarse aggregate. Various forms of ceramic waste are shown in Fig. 1 and Fig. 2.

Fig. 1. The production waste

Fig. 2. The household and building waste

B. X-ray diffraction

The main requirement for aggregates is that they should not be alkaline and not react with cement or be pozzolanic. To find out whether the ceramic waste aggregate reacts with the cement, an X-ray diffraction test is performed. The initial step is mashing the ceramic waste aggregate until smooth with a maximum grain size of 0.3 mm. Then, mix the ceramic waste aggregate that has been crushed with enough water to become a concrete mixture. Make to specimens with a size of 5 mm x 5 mm. In comparison, specimens are also made with normal aggregates. Place the test object in a wet or damp room until 28 days old. Finally, the specimens are tested by X-rays after the age of 28 days.

C. Testing Methods

Concrete aggregate material that will be used as an aggregate must go through a series of tests. Testing the mechanical properties of concrete aggregates must be based on applicable standards, such as ASTM, SNI, BSI, and so on. Types of tests conducted on ceramic waste aggregates include chemical composition test, absorption, and water content test based on ASTM C 33-03 [16], specific gravity test based on ASTM C 127 [17], Soundness test based on ASTM C 88-99a [18] and testing of the soundness on ceramic waste aggregates shown in Fig. 3, abrasion test based on ASTM C 131-01 [19] and testing of the abrasion and impact on ceramic waste aggregates shown in Fig.5, granular form test based on BS 812-105.2 [20] and testing of the granular form on ceramic waste aggregates shown in Fig.4, and gradation test based on ASTM C 33-03 [16].

Fig. 3. Testing of the soundness or weathering on ceramic waste aggregates.

Fig. 4. Testing of the granular form on ceramic waste aggregates

Fig. 5. Testing of the abrasion and impact on ceramic waste aggregates.

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III. RESULTS AND DISCUSSION

A. Chemical Composition

From the results of chemical tests on the ceramic waste aggregates show that ceramic waste aggregates consist of beneficial and detrimental elements in concrete. Ceramic waste aggregate contains elements Feldspar ($KALSi_3O_8$) and Silicate (SiO_2), both of these compounds are silicate compounds that have high hardness but can cause cracks in concrete and have low tensile strength. Concrete aggregates that contain a lot of silicates cause the concrete to be ductile or brittle, but it has high compressive strength. From the results of the hardness test (abrasion test), it is evident that the ceramic waste aggregate has a relatively small percentage of damage that is 17.88%. Other elements contained in the ceramic waste aggregate include AL_2O_3, CaO, Na_2O, and Fe_2O_3. These elements are oxide compounds commonly found in cement, so they do not have a negative impact on concrete.

B. Water content, specific gravity, and Absorption

Based on Table 1, normal aggregates have greater water content than the ceramic waste aggregate (CWA) which is 4.78% for normal fine aggregate and 3.87% for CWA fine aggregate, 4.03% for normal coarse aggregate and 3.10% for CWA coarse aggregate. This is due to the greater porosity or cavities in the normal aggregate, and is evidenced by the absorption rate of normal aggregates is greater than that of ceramic waste aggregates (CWA). However, this is not fully a reference in determining the water content, because it still depends on the aggregate environment conditions and aggregate conditions when tested, such as wet, dry face and so on.

Absorption of aggregate on the water depends on the pores, if the aggregate has large pores, then absorption will also be large. On absorption examination, the normal aggregate has greater absorption than the CWA aggregate which is 1.58% for normal fine aggregate, 0.51% for CWA fine aggregate, and 3.95% for normal coarse aggregate and 3.01% for CWA aggregate. This is because the normal aggregate pores are greater than the CWA aggregate.

Table-1: Quality data of fine aggregate and coarse aggregate

Measuring parameters	Normal fine aggregate	CWA fine aggregate	Normal coarse aggregate	CWA coarse aggregate
Water content	4.78 %	3.87 %	4.03 %	3.10 %
Specific gravity	2.62	2.26	2.62	2.13
Water absorption	1.58%	0.51%	3.95%	3.01%
Unit weight	1.609 gr/cm^3	1.561 gr/cm^3	1.531 gr/cm^3	1.509 gr/cm^3

For specific gravity testing, normal aggregates have a specific gravity greater than CWA aggregate which is 2.62 for normal fine aggregate, 2.26 for CWA fine aggregate. For normal coarse aggregate specific gravity 2.62 and CWA coarse aggregate 2.13. From the description above it appears that the normal aggregate and CWA aggregates fall into the category of normal aggregates which have a specific gravity between 2-2.7. But for the CWA aggregate, it is quite light in the normal aggregate category because the normal aggregate ranges from 2.5-2.7.

C. Soundness

This test aims to estimate the level of soundness when subjected to weathering action in concrete or other applications. The nature of the aggregate resistance to the influence of weather is called weather resistance or eternal shape. This property is an indication of the aggregate ability to withstand excessive volume changes caused by changes in environmental conditions, such as freezing, thawing, temperature changes, the rainy season, alternating dry seasons and so on.

Table 2 shows data from research results based on the ASTM C 88-99a [18], standard, namely by immersing ceramic waste aggregates in a solution of magnesium sulfate ($MgSO_4$). The percentage of weathered aggregate is 1.484%. This shows that the aggregate of CWA can be used as a concrete aggregate because it meets the ASTM standard of maximum weathering of 18%.

Table-2: Data of soundness test results

Specimens	Weathered aggregate (%)	Average (%)
I	1.10	
II	2.15	
III	1.50	1.484
IV	0.80	
V	1.87	

D. Abrasion and impact

Aggregate hardness is important for concrete materials because aggregate hardness greatly affects the strength of the concrete, especially its compressive strength. Hardness testing is carried out based on ASTM C 131-01 [19] standard, namely by using the Los Angeles Engine. Table 3 shows the data from the abrasion test and obtained the average value of the destroyed percentage of the CWA aggregate was 17.88%. The percentage of the test results shows that the CWA aggregate meets the ASTM standard with maximum wear out the limit of 40%. From the limitations provided by the ASTM standard, aggregate ceramic waste can be used as concrete aggregates in this study.

Table-3: Data of abrasion and impact test results

Specimens	the aggregate of losses (%)	Average (%)
I	17.92	
II	18.04	
III	17.66	17.88
IV	17.48	
V	18.28	

E. Granular form

Aggregates can have various forms of granules, such as round, angular, flat, oval or long. The ceramic waste aggregate has a sharp, flat, slightly oval shaped granular shape, and there is a slippery surface.

This is because ceramic waste comes from fragments of goods that have flat and sharp shapes.

Table-4: Data of granular form test results

Specimens	Flakiness index (%)	Elongation index (%)
I	19.53	6.65
II	19.10	6.78
III	21.58	6.40
IV	21.64	7.14
V	20.51	7.29
Average	20.47	6.85

The research of this grain shape is based on the BS 812-105.2 [20] standard: part 3. The standard limit of the maximum grain shape index according to BSI is 20%. Table 4 shows the results of granular form testing. The flakiness index is 20.47% and the elongation index is 6.85%. From the results of this test, it shows that the CWA aggregate is sufficient to meet the standard so that it can be used as a concrete aggregate in this study.

F. Gradation

From Table 5 the normal fine aggregate fineness modulus is 3.16 and the fine aggregate of CWA is 3.69. The fineness modulus of normal coarse aggregate is 6.25 and the coarse aggregate of CWA is 6.14. Table 5 shows the normal aggregate and coarse aggregate CWA meets the ASTM standard, while the fine aggregate CWA does not meet. Therefore, the fineness modulus is calculated based on the combined aggregate of normal fine aggregates with CWA fine aggregates. Table 5, shows the combined aggregate fineness modulus already meets ASTM standards.

Table-5: Data of gradation test results

Type of aggregate	Fineness modulus	Standard limit (ASTM)
Normal fine aggregate	3.16	2.0 - 3.5
CWA fine aggregate	3.69	2.0 - 3.5
Normal coarse aggregate	6.25	6.0 - 6.9
CWA coarse aggregate	6.14	6.0 - 6.9
Combined fine aggregate	3.54	2.0 - 3.5
Combined coarse aggregate	6.17	6.0 - 6.9

Based on ASTM standards the fineness modulus for fine aggregates is 2.0-3.5 and for coarse aggregates 6.0-6.9. For the normal fine aggregate gradation zone and the CWA fine aggregate zone including zone I (coarse sand). Whereas the normal aggregate gradation zone and the CWA coarse aggregate gradation zone include zone III (fine gravel) with a maximum grain size of 9.6 mm and a minimum of 4.7 mm. From Fig. 6 and Fig. 7 shows that the combined aggregate gradation zone meets the percentage of the gradation zone boundaries, namely zone I and zone III. From the description above, the normal aggregate and CWA aggregates can be processed and used as normal concrete mixtures in this study.

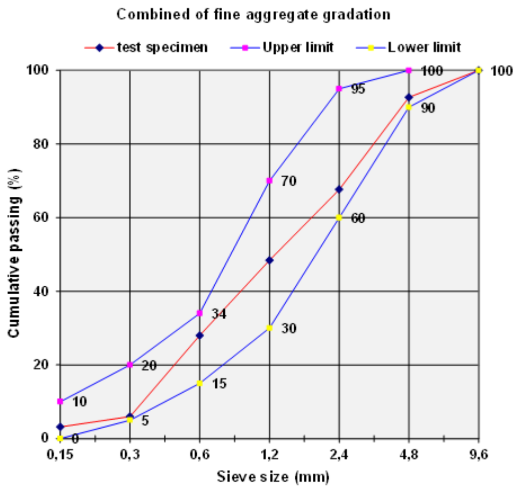

Fig. 6. Gradation curve for combined fine aggregate

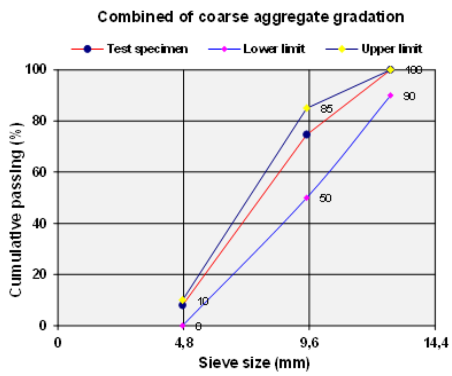

Fig. 7. Gradation curve for combined coarse aggregate

G. X-ray Diffraction

The results of the X-ray Diffraction test for two specimens, namely concrete from normal aggregate and concrete from ceramic aggregate are shown in Table 6.

Table-6: The test result of phase identification with X-ray diffractometers

Number	Type of Concrete	Identified Material	Information
1	Concrete of normal aggregate	a. Portlandite, syn b. Anorthite, Sodian, Intermediate	Testing with powder method
2	Concrete of ceramic aggregate	a. Portlandite, syn b. Quartz c. Calcium Silicate Hydrate d. Dioxolan Hydrate e. Copper Nitrate Hydrate	Testing with powder method

The results of the X-ray diffractometer identification test clearly showed the presence of different elements difference between normal concrete and ceramic waste aggregate concrete as shown in Table 6, Fig.8 and Fig. 9. Normal concrete contains elements of Portlandite [$Ca(OH)_2$] Sodian, Anorthite, and intermediate [$(Ca,Na)(Si,Al)_4O_8$]. Ceramic waste aggregate concrete contains elements of Portlandite [$Ca(OH)_2$], Quartz [SiO_2], Calcium Silicate Hydrate [$Ca_1.5SiO_3.5!\ XH_2O$], Dioxolan Hydrate [$C_3H_6O_2!\ 17H_2O$], Copper Nitrate Hydrate [$Cu(NO_3)2!6H_2O$].

From Table 6, Fig.8 and Fig. 9 do not indicate the presence of elements that can react with cement or damage concrete such as alkali, acid, sulfate and chlorite, both in normal concrete and in the aggregate concrete of ceramic waste.

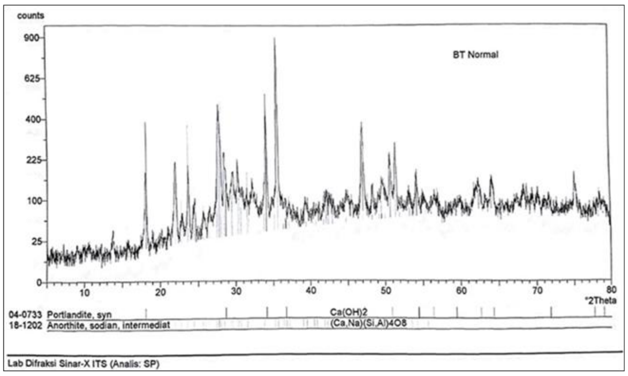

Fig. 8. The identification of normal concrete with the X-ray

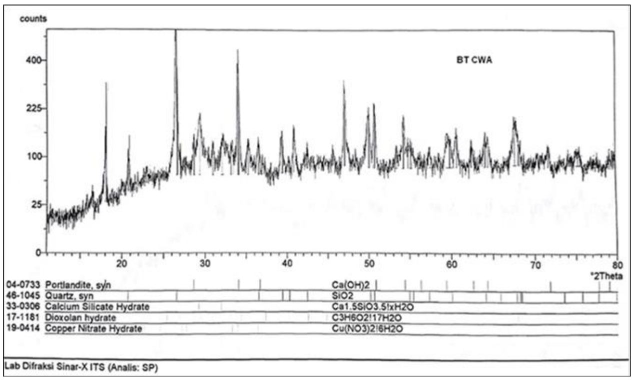

Fig. 9. The identification of ceramic concrete with the X-ray

Elements such as Anhydrite [$CaSO_4$], Barite [$BaSO_4$], Gypsum [$CaSO_4.2H_2O$], and Alunit [$Kal_3(OH)_6(SO_4)$] are common ingredients containing the element sufat. While the element Opal [$SiO_2.nH_2O$] or Silicate Acid [$Si(OH)_4$] is active or amorphous silica that can react with alkaline cement such as [Na_2O and K_2O]. Active silica or amorphous silica are commonly found in materials such as Phyllite, Metadolerite, Granite, Dacite, and Quarsite. But in concrete with ceramic waste aggregate, there is only silica or quartz [SiO_2] which is not reactive to alkaline cement. And also in concrete with ceramic waste aggregate, there is no pozzolanic silica element that can react with cement such as $Na(OH)_2$ produced from the hydration process of C_3S and C_2S, to produce new CSH gel (CSH-2 gel) such as Eq. (1) and Eq. (2) below:

$$2(3CaO.SiO_2) + 6H_2O \Longrightarrow 3CaO.2SiO_2.3H_2O(gelCSH1) + 3Ca(OH)_2 \quad (1)$$

$$Ca(OH)_2 + SiO_2(SF) + H_2O \Longrightarrow gelCSH - 2 \quad (2)$$

The materials found in the ceramic waste aggregate concrete are Calcium Silicate Hydrate, Dioxolan Hydrate, and Copper Nitrate Hydrate cases which function as fillers and not damage the concrete. Dioxolan is a compound on the surface of ceramics that functions as a glossy. Copper compounds found on the surface of ceramics are coating materials that function as glazes. And these compounds are percentage very small as shown in Fig. 6.

IV. CONCLUSIONS

From the results of testing of mechanical properties of ceramic waste aggregate materials obtained several conclusions:

- Based on tests of mechanical properties, ceramic waste materials can be used as concrete aggregate materials but must attend to the maximum gradation according to the thickness and slippery surface of the ceramic waste.
- To overcoming the problem of industrial and residential waste, especially ceramic waste can be done by utilizing it as a concrete aggregate but must pay attention to economic and performance aspects.
- The X-ray test results show that concrete aggregates from ceramic waste are not pozzolanic and there are no elements that can react with alkaline cement, so they can be used as concrete aggregates

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