Effects of using metal granules on strength and stiffness

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Abstract. Using metal granules, which are waste products of the metal industry, as a replacement material in mortars, is economically productive and environmentally beneficial because it contributes to reduction of the amount of the metal waste. It was attempted to develop and produce metal granule reinforced cementitious composite instead of using conventional fibers. Metal wastes bonded to the matrix with the help of adhesion effect is aimed to improve the mechanical and deformation properties of the mortar. As the amount of metal waste increased in the mortar, the compressive strength of the mortars except those with 10\% granules enhanced. The rise in the maximum stress values of the samples and the growth in the modulus of elasticity were similar. 30\% metal waste mortar demonstrated the highest value of compressive strength and modulus of elasticity in this study.

1. Introduction
As the human population continue to increase, there is a boost of productions. This leads to a rise of production waste as well. For this reason, many substances are found in soil, air and water that threat the health of living things. As time passes by, difficulty appears in eliminating and storing such materials. This pollution in nature also causes economic hardship. Consequently, the reuse of these substances, which industrial wastes (such as slag and metal granules) are the part of, has become the subject of scientific studies. Recently, various studies have been carried out especially on the use of metal granules instead of metal fibers. This may be attributed to the low price of metal granules, that is a by-product of the lathes, compared to metal fibers [1].

Depending on their characteristic, the recycled aggregate produced from construction and demolition wastes can be used in different engineering works that can help circuitously the economic and environmental sustainability of the various countries. With further research and development to overcome technical and market barriers, a meaningful increase in improvement rates can be achieved with current technologies in developed economies [2].

In pig iron production, the impurities in the iron sprout, coke ash and the residues from burning of limestone form slag. The slag obtained from the furnace takes the grain structure according to the cooling method. When it is cooled slowly in the air, it has a crystal structure. It is almost completely glassy when it is cooled in water. The total amount of CaO, MgO and SiO\textsubscript{2} in the slags is expected to be at least 67\% [3].

For the safety, durability and utility of structural materials, compressive strength and the elastic properties are the most important parameters [4]. They are used in some cases to fulfill eventual requirements and serviceability limit position such as in the design of pre-stressed concrete structures. Particularly, these parameters come into prominence in risky earthquake zones. Obtaining the compressive strength of a building material is not only important input for the strength of the materials.
For example, approximations might be made about the volume of pores in a known material if the compressive strength is attained. The modulus of elasticity allows us to get information about stiffness of a material. The stiffness enhances due to the tangent of the slope in linear area of the strain-stress curve rises.

The slag obtained by different methods are used in cement based composites as binder or aggregate considering the grain size. The granulated blast-furnace slag had been used in concrete as binder instead of cement, resulted in high performance in terms of long-term strength in concrete [5]. Electric arc furnace (EAF) steel slag produced which currently account for more than 40% of global steel production is still recognized as a solid waste by-product that needs to dispose of. Several studies have been accomplished to characterize EAF steel slag with respect to its application in the construction industry such as its attributes as an additive material and having a great potential for development in the existence of cement mineral compounds [6].

On a study, metal granules in a cementitious composite were determined the roles to ensure what points they can replace traditional fibers. As a result of the tests, it was achieved that compressive strength of the cementitious composite reinforced metal granules was more 18% than the traditional concrete [7].

Mortar, which is a building material obtained at the desired consistency, granulated aggregate (which its maximum size is 4.75 mm), cement as a binder, enough water and additive supplemented as required are homogeneously mixed. The properties of the mortar depend on the aggregate, matrix, metal reinforcement as well as the zone between the aggregate and matrix, and the metal and matrix. These zones state many of the important properties of mortar, such as strength and cracking behavior.

The aim of this study was to explore new fields by using waste materials, to obtain values by analyzing the effects of metal granules on strength and stiffness of the mortar, and to be able to lead to further studies if efficient results were achieved. It might be also economically beneficial to reuse wastes instead of stocking or disposing. Experimental scope was that the results were collected about the strength and hardness of the samples by compressive strength test.

2. Materials and method

2.1. Materials

The materials involving in the mixture were first put in the oven at 105±5 °C until the moisture was removed before mixing. In this study, slag was provided by Ferrokrom Factory. The slag with a maximum grain size of 4 mm was used as aggregate in the mortar samples. The metal granules were substituted at certain ratios. The metal granules with the same chemical compositions and properties were used at ratios of 10% and 30% by volume in 10% intervals. CEM I 42,5 R was used as a binder in the blends. Table 1 presents the mix proportions of mortars.

The blend was mixed in a benchtop laboratory mixer. Due to the different physicochemical properties of the components, super plasticizer was used as needed. As a result of the test mixes for the production, suitable component ratios, strength and workability were taken into consideration and in order to be able to compare results of the mixtures, while the flow diameter was kept at a certain range in the consistency table test. Thus, the cement dosage and water / cement ratio were determined as 400 kg / m³ and 0.7, respectively. Beyond 30% of metal granules addition caused segregation. Thus, the maximum limit of the amount of granule replacement was determined as 30%.

Each mixture was placed in the steel molds after it became homogeneous in the mixer. The surface of the mold was covered with plastic foil and the samples were kept in for 24 hours to let them set and harden. In this step, plastic foil was used to prevent the loss of water required for hydration. The dimensions of the solid samples were 40x40x160 mm.

As soon as demoulding, solid samples were allowed to cure in the tank filled with water, which its temperature was 20±2 °C. After curing for 28 days, the samples were taken from the curing tank. Then, they were stored in laboratory conditions at 22±2 °C for 4 hours before the test.
Table 1. Mix proportions of mortars.

|          | Cement (kg/m³) | Water (kg/m³) | Metal granules (kg/m³) | Slag (kg/m³) | Super plasticizer (kg/m³) |
|----------|----------------|---------------|------------------------|--------------|--------------------------|
| M0       | 400,0          | 417,4         |                        | 1716,4       | -                        |
| M10      | 400,0          | 376,8         | 419,0                  | 1209,0       | -                        |
| M20      | 400,0          | 390,6         | 837,9                  | 1381,7       | 4,0                      |
| M30      | 400,0          | 376,8         | 1256,9                 | 1554,4       | 6,8                      |

2.2. Method

The prism samples were used to determine the compressive strength and modulus of elasticity. The compressive strength tests were performed and the modulus of elasticity calculated at 28 days for each mortar which were divided into two pieces by flexural strength test. The compressive strength was examined by displacement controlled hydraulic press. The pace rate was 2 mm per a minute. At least, 3 specimens were determined each test.

The modulus of elasticity was concluded by stress – strain curve. The modulus can be determined by some other calculation methods as well [8]. Equation (1) is eligible to find the modulus of elasticity in this study [9].

\[ E = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1} \] (1)

Where:
- \( \sigma_1 \): stress at a longitudinal strain
- \( \sigma_2 \): stress at 40% of ultimate load
- \( \varepsilon_1 \): of 5x10⁻⁶⁵
- \( \varepsilon_2 \): longitudinal strain produced by stress \( \sigma_2 \)

The bulk density and volume of permeable pore space rates were obtained by testing prism samples according to ASTM C 642 [10]. ASTM C 109 was used to plot the stress-strain curves [11].

3. Results and discussion

3.1. Compressive strength results

The compressive strength test results are presented in Table 2. The compressive strength values of M0, M10, M20 and M30 were specified 14.15, 13.76, 17.91 and 18.61 MPa, respectively. In comparison with M0, while compressive strength of M30 and M20 incremented by 31.52% and 26.57% respectively, M10 resulted in 2.76% reduction. Using metal waste powders didn’t perform well in a study [12]. Replacement aggregate with certain percentages made the mortars compressive strength regularly down. %8 metal existence caused the most reduction. Also in another study [1], it was declared that %3 metal presence lowered the compressive strength by %1.51.

Compressive strength is related to the quantity of voids in a sample. It can be assumed that a rise in compressive strength can be generally achieved by lessening of porosity in the mortars [13]. The existence of metal granules in the mortar resulted in development at the strengths of other mixtures, except M10. Although the volume of permeable porosity gives information about the spaces inside the mortars, it does not reflect actual situation about the total porosity. Because the rate of closed porosity is not exactly known by the method. The strength reduction in the M10 might be caused by a large number of closed porosity compared to the reference samples’. Besides that, these results were only data obtained by curing for 28 days. Although it is not indicated here, M10 was slightly higher than M0 in
the test results of 90-day samples. Standard deviation of M0 and M10 are 1.00, 0.82, respectively. Since the values are close to each other, it is possible that the results remain unchanged.

|        | Oven dry bulk density | Volume of permeable pore space (%) | Compressive strength (MPa) | Modulus of elasticity (GPa) |
|--------|-----------------------|-----------------------------------|---------------------------|-----------------------------|
| M0     | 2.18                  | 22.95                             | 14.15                     | 7.23                        |
| SD     | 0.04                  | 0.34                              | 1.00                      | -                           |
| M10    | 2.21                  | 28.92                             | 13.76                     | 10.27                       |
| SD     | 0.02                  | 1.01                              | 0.82                      | -                           |
| M20    | 2.48                  | 27.09                             | 17.91                     | 12.76                       |
| SD     | 0.03                  | 0.11                              | 0.43                      | -                           |
| M30    | 2.61                  | 25.96                             | 18.61                     | 14.16                       |
| SD     | 0.02                  | 0.35                              | 0.30                      | -                           |

*Standard deviation

3.2. The modulus of elasticity

Stress – strain curves, which were presented in figure 1, were obtained as a result of the compressive strength test. The modulus of elasticity was calculated by equation (1) for each mixture. The values of the modulus were exhibited on table 2.

Considering the modulus of elasticity at the samples, M30 had the highest rate as 14.16 GPa. The ascent rates of M20, M10 in modulus of elasticity were 76.65% and 42.15%, respectively, while comparing the other mortars with the reference mortar (M0). This rate reached 95.96% for M30.

While comparing slag aggregated concrete with traditional concrete, slag affected slightly decrease on the modulus of elasticity [14]. It was explained that slag porosity was higher than the natural aggregate.

The modulus of elasticity of M10 reached higher ratios while the strength was low than M0, because the stiffness of the metal granules was higher than the slag.

Compressive strength is not the only influence on achieving for the modulus of elasticity. Such as volumetric ratio, considerably affects cementitious composites strain due to the anisotropic structure of materials [15]. The interface between aggregate and cement paste is an important parameter in the elastic behavior of the composites as well.

![Stress-strain curves of the mortars](image-url)
4. Conclusions
In the study, using metal granules in mortars remarkably enhanced their modulus of elasticity values. Especially, M30 had the highest values under the load. Although the metal existence in the mortar enhanced the volume of permeable pore spaces, the modulus of elasticity did not lower their performance. As the strain parameter in the graph was taken into consideration, metal granules allowed to more rigid property gain for mortars. If the 28 days M10 slight strength drop was ignored, the presence metal granules caused an effective rise in terms of strength and stiffness. While the curves of M20 and M30 on figure 1 were observed, the strength and the stiffness approached the same behaviours.

The optimum solution for this study is related to workability and compressive strength. Maximum strength and stiffness were achieved at 30% volume fraction within an acceptable range.

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