Performance of Recycled Coarse Aggregate Concrete Incorporating Metakaolin

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Abstract. The civil engineering industry is currently facing significant challenges of how to be an eco-friendly industry. The thoughtful utilization of natural resources in construction practices and the usage of recycled materials in the production of concrete can be a solution. In this experimental study, the behavior of recycled aggregate concrete (RAC) incorporating 100% recycled coarse (RC) aggregate is examined. It investigates the workability and mechanical properties of concrete after total replacement of natural coarse (NC) aggregate with RC aggregate. The influence of using Metakaolin (MK) at contents of 4, 8, 12, 16, and 20% on RA concrete performance is assessed. In total six mixes (one without MK and five included MK). A reference mix made with NCA was also prepared for comparison reasons. Workability, mechanical properties, water absorption (WA), and dynamic modulus of elasticity (Ed) were determined. The obtained results reveal that MK reduces the workability of the RAC. However, MK results in compressive strength enhancement and dynamic modulus of elasticity improvement, and lower water absorption of recycled aggregate concrete.

Keywords: Metakaolin; compressive strength; dynamic elastic modulus Ed; UPV; recycled aggregate concrete.

1. Introduction

Due to economic growth and social development, urbanization is on continuous rapid development. This urbanization demands the use of vast quantities of construction materials. One of the most used materials as constructional materials is concrete. However, the use of concrete is accompanied by many sustainability issues and environmental concerns that are well-known worldwide. Today, it is obvious that Portland cement production is blamable for significant amounts of CO\textsubscript{2} in our environment [1,2]. Also, the accumulation of vast quantities of waste materials, particularly the construction and demolition of concrete structures, causes another environmental issue. The disposal of this massive volume of waste materials needs large areas as landfill, which is in shortage in most countries [2–4]. Additionally, the shortage in the natural recourses of coarse (NC) aggregates used in the manufacturing of concrete is also a concern. Henceforth, the utilization of cement replacement materials such as Metakaolin (MK) to
reduce the use of cement needed to produce concrete can considerably help in alleviating some of the environmental issues [3,4]. The coupling of using MK (instead of part of cement) with the use of recycled coarse (RC) aggregate instead of natural coarse (NC) aggregates in the production of concrete could lead to a significant sustainability enhancement of concrete. Waste resources such as demolished concrete structures can be used as aggregate in concrete. Such concrete debris extracted from demolished structures can be processed and used as recycled aggregates RA in concrete.

The behavior of concrete incorporating RC aggregate has been a hot topic to investigate by many scholars [4-13]. These investigations have revealed that the utilization of RC aggregate can result in concrete with low quality. The use of RC aggregate diminishes the mechanical characteristics and reduces concrete’s workability [4,7-9]. It is reported that mechanical properties encompassing splitting tensile strength, compressive strength, and flexural strength of concrete incorporating RC aggregate are lower than those made with NC aggregate. Reduction ratios of up to 40% in compressive strength, 20% in splitting tensile strength, and 15% in flexural strength are reported [5, 6, 9,12]. The studies have shown that these reductions are due to RC aggregate weakness, which has properties such as low density and high-water absorption WA [5,8,11,13]. These adverse properties, particularly low density, and WA, also result in the concrete's low workability made with recycled coarse aggregate [11,13].

The positive influences of employing MK on the behavior of concrete made with NC aggregate are well-established [14]. It is well known that metakaolin is characterized by a pozzolanic reaction when mixed with water. The utilization of MK can enhance the mechanical properties and improve the durability of natural aggregate concrete NA concrete [14,15]. This pozzolanic reaction, which produces more calcium silicate hydrate (C-S-H) that ensures the redevelopment of cement paste and concrete strength, is the main reason for these strength durability enhancements [16,17]. The studies that deal with the influence of incorporating MK on the performance of concrete made with 100% recycled coarse aggregate are few [18]. Therefore, the current study examines the influence of using MK on the behavior of concretes made with 100% RC aggregate. This study tackles the workability, density, compressive strength, and water absorption of the recycled aggregate (RA) concrete made with RC aggregate. Slump test, compression test, density, and water absorption tests were conducted. Also, ultrasonic pules velocity (UPV) was carried out to determine the dynamic modulus of all investigated concrete mixtures' elasticity.

2. Experimental Procedure

2.1 Concrete Materials

Ordinary Portland cement type CEM I was used in the current study. It complies with the specifications of BS EN 197. The chemical analysis of the cement (as specified by the provider) is shown in Table 1, whereas the physical properties of OPC are presented in Table 2.

| Material (%) | SiO₂ | Al₂O₃ | Fe₂O₃ | CaO | MgO | SO₃ | Na₂O | K₂O | Na₂O |
|--------------|------|-------|-------|-----|-----|-----|------|-----|------|
| CEM I        | 20.88| 4.98  | 2.96  | 65.7| 0.76| 2.82| 0.28 | 0.44| 0.50 |
| MK           | 57.6 | 30.1  | 6.6   | 1.0 | 0.98| -   | -    | 0.58| -    |

| Binder/Property | Specific gravity | Fineness (cm²/kg) | Color | Initial setting time (min) |
|-----------------|------------------|-------------------|-------|---------------------------|
| CEM I           | 3.15             | 2400              | Grey  | 100                       |
| MK              | 2.5              | 12800             | White | -                         |

Metakaolin (MK) was used in this study as reactive mineral admixtures to replace OPC. The chemical composition and some MK's physical properties (as provided by the dealer) are displayed in Table 1 and Table 2, respectively. Coarse and fine aggregates were used in this study. The fine aggregate
was local river sand brought from the Kalak area near Erbil City-Iraq. It had a maximum size of 4.75 mm. The NC aggregate was obtained from the same area. It was a naturally rounded river aggregate. Another type of coarse aggregate was used in this study which is RC aggregate. It was RA obtained from crushing old concrete portions, which are rubbles that resulted from the demolishing of old concrete structures (see Figure 1). The physical properties of both types of coarse aggregates are presented in Table 3. Both types of coarse aggregates had the same maximum size of 19.5 mm.

Table 3. Physical characteristics of coarse aggregate (CA) used in the current study.

| Type of CA | Specific gravity (SSD) | Water absorption (%) | Shape | Surface texture |
|------------|------------------------|----------------------|-------|----------------|
| Natural    | 2.63                   | 1.0                  | Rounded | Smooth         |
| Recycled   | 2.44                   | 4.1                  | Angular | Rough          |

Figure 1. Recycled coarse aggregate.

2.2 Mix proportions, casting, and specimen’s details
The total number of mixes prepared in this study is seven. Table 4 illustrates the mixtures details, such as the code of mixtures, variables of the study, and the mix proportions for all mixtures. All mixtures had similar water/cement (w/c) ratio of (0.46).

Table 4. Variables of study, code of mixes, and mix proportions (kg/m³).

| Mix Designation | Metakaolin content (%) | Cement | Metakaolin | Water | Coarse Agg. (natural) | Coarse Agg. (Recycled) | Fine Agg. |
|-----------------|------------------------|--------|------------|-------|-----------------------|------------------------|-----------|
| NAC             | 0                      | 375    | 0          | 172.5 | 1092                  | 0                      | 711       |
| RAC0            | 0                      | 375    | 0          | 172.5 | 0                     | 1026                   | 711       |
| RAC4            | 4                      | 360    | 15         | 172.5 | 0                     | 1026                   | 711       |
| RAC8            | 8                      | 345    | 30         | 172.5 | 0                     | 1026                   | 711       |
| RAC12           | 12                     | 330    | 45         | 172.5 | 0                     | 1026                   | 711       |
| RAC16           | 16                     | 315    | 60         | 172.5 | 0                     | 1026                   | 711       |
| RAC20           | 20                     | 300    | 75         | 172.5 | 0                     | 1026                   | 711       |

*By cement mass

The concrete constituents were mixed using a pan mixer which had a capacity of 0.08 m³. An internal vibrator was used to compact the concrete mixtures. Different types of specimens were cast for each mix. Three 100 mm cube samples, three cylinders 100×200 mm samples, and three prisms 100×100×400 mm were cast for each mix. After the completion of the concrete casting, samples were protected by plastic sheets to avoid loss of moisture and endorsed to cure for 24 hours before mold removal. After that, the specimens were further cured by putting them in water tanks at room temperature for 27 days.
3. Tests

The workability of all mixes was evaluated through a well-known standard slump test. It was conducted as per the BS EN 12350-2 [19]. The compressive strength test for all cubes of the mixtures was performed using a 2000 kN hydraulic machine. All cubes were cured at water curing for 28 days. At the age of testing, the test was conducted in accordance with the BS EN 12390-3 standard test [20]. In order to measure the density and water absorption WA of concrete specimens of all mixes, the standard tests proposed by ASTM were followed. These tests were undertaken by following the ASTM C642-06 [21]. Cubic specimens with dimensions of 100x100x100 mm at the age of 28 days were used in these tests. Three specimens were used for each test. At the end of the curing period, all specimens were dried for 24 hours in the oven at a temperature of 100-110°C. Then, the specimens were taken out of the oven and kept to cool in the dry air at room temperature, and then they were weighed. The value that is obtained is denoted as (d). After the process of drying, the specimens were put in a container immersed in water, and boiled for about 5 hours, and left in the water for 24 hours. After this, the surface moisture was also removed by a towel, and the specimens were weighted. The value that is obtained is denoted as (m). After immersion and drying oven, the specimens were immersed in water by a wire attached to the balance and calculate the weight immersed in water and denoted as (s). The bulk density and water absorption were determined using equations 1 and 2, respectively:

Bulk density, dry = \( \frac{d}{(m-s)} \times \gamma \)  

Water absorption, % = \( \frac{(m-d)}{d} \times 100 \)

where:

- \( d \) = mass of specimen in air in oven-dried condition, g
- \( m \) = mass of specimen in air after the immersion and boiling in surface-dry condition, g
- \( s \) = apparent mass of specimen in water after the immersion and boiling, g
- \( \gamma \) = water density

As a non-destructive test of concrete, the ultrasonic pulse velocity (UPV) test was carried out to obtain the dynamic modulus of elasticity (Ed) of concrete. In the current study, the device used was type PUNDIT with a frequency 55 kHz and an accuracy of 0.1 km/sec. The test was conducted following the standard test of ASTM C597-09 [22]. This test is employed to assess the uniformity of concrete and expose its flaws, such as the presence of cracks and voids, by determining the longitudinal vibration wave that passes through the tested concrete. Also, this test is used to calculate the dynamic modulus of elasticity (Ed). UPV value is calculated by dividing the required time (T) for the wave to pass a distance (L) in the specimen, as presented in Figure 2. The dynamic modulus of elasticity of concrete (Ed) can be determined from the results of the UPV test based on the Eq. (3):

\[
Ed = \frac{\rho v^2 (1+\mu) (1-2\mu)}{(1-\mu)}
\]

Where Ed = dynamic modulus of elasticity (MPa); \( \rho \) = density of concrete (kg/m³); \( v \) = ultrasonic pulse velocity (km/s); and \( \mu \) = assumed Poisson’s ratio = 0.20.

![Figure 2. Ultrasonic pulse velocity test.](image-url)
4. Results and discussion

4.1 Workability

All concrete mixtures in the fresh condition were assessed for their workability. The standard slump test evaluated the concrete mixture’s workability. The results of the slump test in mm are shown in Table 5 and Figure 3. The negative effect of replacing NC aggregate with RC aggregate on the workability of concrete is clear in Figure 5. It can be understood that the value of slump of the mix NAC declined from 125 mm to 80 mm when the NC aggregate was totally replaced with RC aggregate as in mix RAC0. NAC mix lost around 36% of its workability when RCA was used. Similar results were reported by [2,4,8]. This decrease in workability may have resulted from that RC aggregate has a higher capacity to absorb water than NC aggregate. This higher absorption capacity results from the heterogeneous nature of RC aggregate particles [1,7,9]. In general, the addition of MK also negatively affects the workability of mixes made with RC aggregate, as can be seen in Figure 3. The workability of the RC aggregate mixes reduced with the addition of MK, and this reduction depends on the content of MK. At MK content of 4%, the RCA mix’s workability showed no change, but when the content of MK increased to 8% and 12%, the slump value dropped to 75 mm. More reduction in workability was observed when at MK contents of 16% and 20%. This reduction workability due to MK’s addition is expected as MK particles decrease the workability due to its high surface area compared to that of the cement particles [14,18].

Table 5. Fresh properties (slump in mm) and compressive strength.

| Mix Number | Mix Designation | Slump (mm) | Compressive strength (MPa) | Normalized strength to NAC* | Normalized strength to RAC0* |
|------------|----------------|-----------|---------------------------|-----------------------------|-------------------------------|
| 1          | NAC            | 125       | 44.8                      | 1                           | -                             |
| 2          | RAC0           | 80        | 31.4                      | 0.70                        | 1                             |
| 3          | RAC4           | 80        | 33.3                      | 0.74                        | 1.06                          |
| 4          | RAC8           | 75        | 35.2                      | 0.79                        | 1.12                          |
| 5          | RAC12          | 75        | 37.4                      | 0.83                        | 1.19                          |
| 6          | RAC16          | 65        | 38.9                      | 0.87                        | 1.24                          |
| 7          | RAC20          | 60        | 40.5                      | 0.90                        | 1.29                          |

*NAC=natural aggregate concrete; RAC= recycled aggregate concrete

Figure 3. Slump values of mixes NAC and RAC0 with the influence of MK content on slump results.

4.2 Compressive Strength

The compressive strength performance of all concrete mixtures with and without MK is discussed. The outcomes of the 28 days compressive strength of all concrete mixtures are depicted in Table 5. The
compressive strength value of each mix is the mean of 3 readings. Table 5 and Figure 4 also represent the normalized strength to the strength of the mixes NAC, and Figure 7 shows that normalized to mix RAC0 (in comparison with that of NAC mix and RAC0 mix).

![Figure 4](image_url)

**Figure 4.** Results of the compressive strength at 28 days for all mixes.

Figure 4 shows that the mix RAC0, which includes RC aggregate, displayed lower compressive strength than that of the NAC mix. Other studies [13,23-25] reported a similar trend. This reduction in strength due to recycled coarse aggregate utilization is about 30% (see Figure 4). This strength loss is expected as the quality of RC aggregate is lower than that of NC aggregate in terms of specific gravity, water absorption, and composition [2,4]. The heterogeneous nature of RC aggregate because of the attached mortar exist on the external surface of the RC aggregate is the main reason for this strength loss. The attached mortar is characterized by low density and high porosity leading to weaker concrete [11,4]. The results presented in Figure 4 represent the normalized strength to that of the reference mix (NAC). In general, the addition of MK decreases the loss in strength because of the use of RC aggregate. This decrease in strength loss depends on the replacement ratio of the MK as illustrated in Figure 4. The strength of the RAC mixes increased to represent 0.74 of that of NAC mix at 4% MK content; whereas, at MK content of 20%, the compressive strength of RAC mix reached 0.90 of that of NAC mix. Hence, the use of 20% of MK in RAC mixes can compensate for the loss in strength caused by the inclusion of RC aggregate, and its strength can reach up to 90% of that of the NAC.

The results of the RAC mixes with MK compared to that without MK (RAC0) are illustrated in Figure 5. The positive effect of the addition of MK on the compressive strength of RAC can be clearly observed. The strength improvement reached 6, 12, 19, 24, and 29% when the MK was added at contents of 4, 8, 12, 16, and 20%, respectively. The main reason behind this strength enhancement could be the positive effect of the pozzolanic reaction of the metakaolin particles, which can lead to more calcium-silicate- hydrate (C-S-H) (the product responsible for the strength of the cement paste) in the structure of the concrete [16,25]. Hence, the utilizing of up to 20% of MK can result in considerable enhancement in the strength of RAC.
4.3 Density

The density of all mixes of the concrete after curing in water for 28 days is displayed in Table 6. The test was carried out per the standard test of the ASTM C642-06, and three specimens were tested for each mix. The results in Table 6 represent the average of three readings.

Table 6. Results of density, UPV, dynamic modulus of elasticity, and water absorption (WA).

| Mix Number | Mix Designation | Density (kg/m³) | UPV (km/sec) | Ed (GPa) | WA (%) |
|------------|-----------------|-----------------|--------------|----------|--------|
| 1          | NAC             | 2362            | 4.62         | 44.2     | 7.1    |
| 2          | RAC0            | 2244            | 4.01         | 31.6     | 9.2    |
| 3          | RAC4            | 2251            | 4.08         | 32.8     | 9.1    |
| 4          | RAC8            | 2250            | 4.10         | 33.1     | 9.0    |
| 5          | RAC12           | 2263            | 4.20         | 35.0     | 8.8    |
| 6          | RAC16           | 2290            | 4.31         | 37.3     | 8.6    |
| 7          | RAC20           | 2296            | 4.35         | 38.1     | 8.2    |

It can be understood that there is a slight decrease in the density of concrete with the use of RC aggregate. A reduction of more than 5% is observed, as can be seen in Figure 6. This reduction can be ascribed to the RC aggregate particles' low specific gravity compared to that of the NC aggregate, as illustrated in Table 3. The addition of metakaolin slightly increases the density of the RAC mixes, and this increase depends on the ratio of the MK, as can be noticed from Figure 6. At the content of 20% of MK, the RAC mix's density can reach up to 97% of that of the NAC mix.

Figure 5. Normalized strength of all mixes to that of RAC0 mix.

Figure 6. Influence of the content of MK on the density of the RAC mixes.
4.4 Water absorption
Table 6 and Figure 7 show the results of the WA of all concrete mixtures at the age of 28 days. The water absorption WA test was carried out as per the ASTM C642-06, and for each concrete mix, three specimens were tested. The results in Table 6 represent the average of three readings.

![Figure 7. Influence of the content of MK on the WA of the RAC mixes.](image)

In general, the results presented in Figure 7 show that the concrete mixes with recycled aggregate without MK display water absorption values higher than the reference mix (NAC). For example, the water absorption of the RAC0 mix was 9.2 %, whereas the WA of the NAC mix was 7.1%. This means that the RAC0 mix has WA higher than that of the NAC mix by 30%. This high WA of RAC mixes could be caused by the RC aggregate particles' diverse nature, which is characterized by permeable microstructure resulting from the adhered mortar [4-6]. Figure 7 also shows that regardless of the MK content, adding metakaolin can promote decreasing the WA of RAC mixes. At low content of MK, the drop in WA of the mixes of RAC is very small, while at high content such as 16% and 20%, the reduction in WA is higher than low content of MK such as 4% and 8%. Due to its high pozzolanic reaction, it is well-known that MK can result in a more densified structure of concrete compared to a mix without MK [16,18]. Hence, this could be why the lower WA of the mixes with MK compared to that without MK.

4.5 UPV and dynamic modulus of elasticity (Ed)
The results of UPV and modulus of dynamic elasticity (Ed) at the age of 28 days are presented in Table 6. In this table, it can be detected that the UPV value of the NAC mix is higher than that of the RAC0 mix. This means that the NC aggregate's replacement with RC aggregate leads to a lower value of UPV. This is because of the low density of the concrete mix with RC aggregate, as the value of the UPV depends on the density of the concrete. The use of the MK increases the values of UPV of the RAC mixes. This increase depends on the content of the MK. The UPV values increase from 4.01 km/s to 4.08, 4.10, 4.2, 4.31 and 4.35 km/sec at MK contents of 4, 8, 12, 16, and 20%, respectively. The increase in UPV value could be attributed to the higher density of the RAC mixes containing MK, as shown in Table 6. The values of the UPV can be utilized to obtain the dynamic modulus of elasticity (Ed) by using equation 3. Figure 8 illustrates the results of the Ed of all mixes. It can be observed that the elastic modulus of the NAC mix is higher than that of the RAC0 mix by 28%. The lower Ed of the RAC0 mix of due to the lower density of this mix and the lower stiffness of the RC aggregate particles compared with the stiffness of the NC aggregate particles. The addition of the MK has a positive effect on the values of the Ed. This positive effect depends on the percentage of the MK, as can be observed in Figure 8. By adding up to 20% of MK, the Ed value of the RAC mix can reach up to 86% of that of the NAC. This enhancement is due to the dense structure of the RAC mixes with MK obtained resulted from the pozzolanic reaction of the MK.
5. Conclusions
The discussion on the investigational results obtained in the current study can lead to the following conclusions:

- As a result of the RC aggregate's high-water absorption, recycled aggregate concrete mixes show lower slump values compared to NAC mixtures. The use of MK at different contents slightly reduces RAC mixtures workability due to the very small size of its particles that need high water content to maintain suitable workability.
- Because of the RC aggregate weakness, the compressive strength of the RAC mixture dropped by 30% compared to the control mix (NAC).
- The use of MK can help to enhance the 28 days’ compressive strength of the RAC mixture.
- The strength enhancement due to the addition of the MK depends on the content of the MK. Up to 20% strength enhancement can be achieved (compared to NAC) if 20% of MK is used. This is because of the pozzolanic reaction of MK.
- The density of concrete marginally decreases with the use of RC aggregate. A reduction of 5% is observed. Such reduction is due to the RC aggregate particles' low specific gravity compared to NC aggregate particles. The employment of MK slightly increases the density of the RAC mixes, which depends on the content of the MK.
- Recycled coarse aggregate concrete mixtures without MK display water absorption values higher than those of the reference mix NAC. Adding metakaolin can result in dropping the WA of RAC mixes. At the low content of MK, the decrease in WA of the mixtures of RAC is very small, while at high content such as 16% and 20%, the reduction in WA is higher than the low content of MK.
- The dynamic modulus of elasticity (Ed) of RAC0 is lower than the NAC mix by 28%. This is due to the lower density of this mix and the lower stiffness of the RC aggregate particles compared to the stiffness of the NC aggregate particles. The addition of the MK has a positive effect on the values of the Ed. This positive effect depends on the content of the MK.

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References
[1] Mehta, P.K. and Monteiro, P.J., 2014. Concrete: microstructure, properties, and materials. McGraw-Hill Education.
[2] Younis, K.H., 2014. Restrained shrinkage behaviour of concrete with recycled materials. Ph.D.
[3] Tam, V.W., Soomro, M. and Evangelista, A.C.J., 2018. A review of recycled aggregate in concrete applications (2000–2017). Construction and Building Materials, 172, pp.272-292.

[4] Younis, K.H. and Pilakoutas, K., “Strength prediction model and methods for improving recycled aggregate concrete”. Construction and Building Materials, 49, 2013 pp.688-701.

[5] Ayser J. Ismail, Khaleel H. Younis, Shelan M. Maruf, “Recycled Aggregate Concrete Made with Silica Fume: Experimental Investigation”. Civ. Eng. Arch. 8(5); 2020;1136 - 1143.

[6] Safiuuddin, M., Alengaram, U.J., Rahman, M.M., Salam, M.A. and Jumaat, M.Z., 2013. Use of recycled concrete aggregate in concrete: a review. Journal of Civil Engineering and Management, 19(6), pp.796-810.

[7] K. H. Younis, 2021 “Metakaolin modified recycled aggregate concrete containing recycled steel fibers,” Mater. Today Proc., Feb. 2021,

[8] Kou, S.C., Poon, C.S. and Agrela, F.,” Comparisons of natural and recycled aggregate concretes prepared with the addition of different mineral admixtures”. Cement and Concrete Composites, 33(8), 201,1pp.788-795.

[9] Gülsan, M.E., Alzebaree, R., Rasheed, A.A., Niş, A. and Kurtoğlu, A.E., 2019. Development of fly ash/slag based self-compacting geopolymer concrete using nano-silica and steel fiber. Construction and Building Materials, 211, pp.271-283.

[10] H. K. Yaba, H. S. Naji, K. H. Younis, and T. K. Ibrahim, “Compressive and flexural strengths of recycled aggregate concrete: Effect of different contents of metakaolin,” Mater. Today Proc., Feb. 2021.

[11] Xie T, Yang G, Zhao X, Xu J, Fang C. A unified model for predicting the compressive strength of recycled aggregate concrete containing supplementary cementitious materials. J. Clean. Prod. 2020 Apr 1;251:119752.

[12] Younis, K.H. and Mustafa, S.M., 2018. Feasibility of using nanoparticles of SiO2 to improve the performance of recycled aggregate concrete. Advances in Materials Science and Engineering, 2018.

[13] Younis, K.H., Amin, A.A., Ahmed, H.G. and Maruf, S.M., 2020. Recycled Aggregate Concrete including Various Contents of Metakaolin: Mechanical Behavior. Advances in Materials Science and Engineering, 2020.

[14] Poon, C. S., Lam, L., Kou, S. C., Wong, Y. L., and Wong, R., 2001. Rate of pozzolanic reaction of metakaolin in high performance cement pastes. Cement and Concrete Research, 31(9), 1301–1306.

[15] Dinakar, P., Sahoo, P.K., Sriram, G., 2013. Effect of metakaolin content on the properties of high strength concrete. Int. J. Concr. Struct. Mater. 7, 215e223

[16] Abbas, R., Abo-El-Enein, S. A., and Ezzat, E. S., 2010. Properties and durability of metakaolin blended cements: Mortar and concrete. Materiales De Construccin, 60, 33–49.

[17] Basu, P. C., Mavinkurve, S., Bhattacharjee, K. N., Deshpande, Y., and Basu, S., 2000. High reactivity metakaolin: A supplementary cementitious material. In Proceedings ICI Asian conference on ecstasy in concrete, 20–22 Nov, Bangalore, India (pp. 237–436).

[18] Muduli, R., and Mukharjee, B. B., 2019. Effect of incorporation of metakaolin and recycled coarse aggregate on properties of concrete. Journal of cleaner production, 209, 398-414.

[19] BS EN 12390-2, 2009. Testing Fresh Concrete Part 2: Slump test. British Standards Institution, London, UK.

[20] BS EN 12390-3, 2009. Testing Hardened Concrete Part 3: Compressive Strength of Test Specimens, British Standards Institution, London, UK.

[21] ASTM C642-06, 2008. Standard test method for density, absorption, and voids in hardened concrete. Annual Book of ASTM Standard, vol. 4.02.

[22] ASTM, D597, 2009. Standard test method for pulse velocity through concrete. West Conshohocken, PA.

[23] Berndt, M.L., 2009. Properties of sustainable concrete containing fly ash, slag and recycled concrete aggregate. Construction and building materials, 23(7), pp.2606-2613.

[24] Çakır, Ö., 2014. Experimental analysis of properties of recycled coarse aggregate (RCA) concrete
with mineral additives. Construction and Building Materials, 68, pp.17-25.

[25] Kadri, E.H., Kenai, S., Ezziâne, K., Siddique, R., De Schutter, G., 2011. Influence of metakaolin and silica fume on the heat of hydration and compressive strength development of mortar. Applied Clay Science, 53, 704e708.