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Strength Properties of Geopolymer Mortar Containing Binary and Ternary Blends of Metakaolin and Manufacturing By-Products

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Abstract

Geopolymer technology is a new sustainable approach for producing mortar without any cement because of the adverse environmental impact of cement production. In addition to the vast amount of energy and hence non-renewable resource consumption in cement production, using waste materials in geopolymer concrete production approach is highly beneficial due the high costs of waste disposal and the effects of landfill on the environment. The waste materials (red mud, rice husk ash, and waste glass powders) which are the byproducts of the manufacturing and agriculture were used as the pozzolanic materials which are the sources of geopolymer production. In addition to these waste materials, metakaolin was also used because it is the most effective pozzolanic material for use in concrete.

Due to the vast amount of waste by-products generated in Turkey, it is critical that the use of these waste by-products is investigated in the construction industry, as they have detrimental effects on agriculture and groundwater. In this study, the mechanical and physical properties (including compressive and flexural strength) of the geopolymer concrete produced, composites of metakaolin and three different waste products were investigated.

Keywords: geopolymer, geopolymer mortar, sustainability, waste materials, strength properties

Introduction

Cement is an extremely important construction material due to its low cost and ease of application with excellent structural performance. The demand for cement is increasing parallel to economic growth and many growing economies are motivated to achieve rapid infrastructure development, which highlights the remarkable growth in cement production (Mishra and Siddiqui, 2014). Through directly generating jobs and supplying the related industries with numerous cascading economic benefits, the cement industry has improved living standards throughout the world. While it has many benefits, the cement industry exerts a negative impact terms of environment and sustainability aspects (Johannes, 2012).

The cement industry is contributing to energy consumption and is one of the major contributors to high CO₂ emissions; therefore, it has a direct impact on climate change. The production of cement also affects health and safety by polluting the air and environment (Ian and David, 2002). The construction sector is responsible for 36% of energy consumption and causes 39% of CO₂ emissions associated with



4. ASIA PACIFIC INTERNATIONAL CONGRESS ON CONTEMPORARY STUDIES

energy consumption when the generation of upstream power is considered (Global Status Report, 2017).

Mishra and Siddiqui (2014) posited that raw materials and energy consumption release different pollutants into the atmosphere, such as dust and a large number of gases. This includes nitrogen oxides (NO_x), carbon dioxide, water, oxygen, and small amounts of dirt, chlorides, fluorides, sulfur dioxide, carbon monoxide, and other smaller amounts of organic compounds and heavy metals. Due to all of these detrimental effects of cement production, its use should be reduced in the construction industry. In order to replace cement, an alternative material to cement should be proposed which has similar properties and reaction characteristics similar to produce high-quality concrete. Geopolymer concrete has been proposed for this purpose to replace cement with alternative pozzolanic materials.

Davidovits (1994) defined geopolymer cement as a new type of inorganic cementitious material that could be used as a significant alternative to Portland cement due to the binding properties resulting from alkali activation. The geopolymer approach has been studied widely in recent years because of its ability to achieve remarkable mechanical, chemical, and physical properties.

Geopolymers consist of three-dimensional amorphous microstructure aluminosilicate materials. The geopolymerization process occurs when the oxides of silicon and aluminum minerals or aluminosilicates are activated by alkaline solution. Materials that are rich in aluminosilicates include calcined kaolinite and industrial waste such as fly ash; bottom ash and rice husk ash are activated by adding sodium hydroxide, sodium silicate, potassium hydroxide or potassium silicate. When industrial waste ashes are reutilized for geopolymer production, the amount of greenhouse gas emitted to the environment can be lowered by 44 to 64% compared with the production of Portland cement (McLellan et al. 2011).

According to the reaction process, two factors exert a direct impact on the final product, namely the aluminosilicate and activator. The properties of solid aluminosilicate directly affect the process of dissolution and the subsequent reaction, while the liquid activator partially or completely dissolves the solid raw material and controls the breaking up and rebuilding of the aluminosilicate structure, polycondensation, and load balance in the reaction process (Duxson et al., 2005). Fly ash, blast furnace slag, and mine tailings and other waste materials contain sufficiently reactive alumina and silica that can be effectively used as a source material for geopolymerization reactions (Weil et al., 2007; Duxson et al., 2005; Duxson et al., 2007).

Jindal (2018) contended that the majority of calcium-based compounds are effective for enhancing the properties of geopolymers at normal room temperature; hence, in addition to the precast industry, these extend the scope of use of geopolymer concrete in general construction applications. The vast quantity of industrial by-products produced from electricity generation, timber production, iron and steel, rice mills, mining industries, and many others represent a significant environmental challenge, as their disposal produces severe environmental and health effects. Fly ash, low ash, silica, boiler slag, and steel slag are examples of these by-products (Alnahhal et al.2017, Y. Kim et al.2017).

Red mud (RM, hereafter) is a waste material which is a by-product obtained as a result of alumina production from bauxite through a mechanism defined as the Bayer process. After the Bayer process, each ton of bauxite produced 35 to 40% of its weight as RM waste. Due to storage problems, the waste exerts a negative impact on the environment. Thus, it is essential to investigate different uses for RM waste to solve this problem. Depending on the composition of the bauxite and extraction method used,



4. ASIA PACIFIC INTERNATIONAL CONGRESS ON CONTEMPORARY STUDIES

the derived RM can contain different amounts of Fe_2O_3 , Al_2O_3 , SiO_2 , TiO_2 , CaO , and Na_2O .

Waste glass powder (GP, hereafter) includes various types of glass derived from different manufacturing processes, including flat, laminated, or tempered glass, borosilicates, transparent or colored glass, incandescent or fluorescent light bulbs, packaging materials, or glass derived from stoning among others (i.e., any type of glass waste from industrial processes, civil construction, or households). When correctly processed, glass waste can be transformed into a new geopolymer matrix used to replace the traditional ones.

Rice husk ash (hereafter RHA) is collected from cultivated crops; since it is associated with rice agriculture, there is high availability of this ash and it could be labeled as a renewable material. While significant additions could be used in alternative materials for cement, the producers of cement still face problems regarding the transportation and production of RHA.

These by-products will be used in addition to Metakaolin (hereafter MK), which is a dehydroxylated form of the clay mineral kaolinite in the temperature range between 500 and 800°C. Kaolinite is a clay mineral with a chemical composition of $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$, indicating that each particle has one layer of tetrahedral silica and one layer of octahedral alumina (Rovnanik, 2010).

Huseien et al. (2018) revealed that when the MK (0 to 15%) is used to replace ground granulated blast furnace slag (hereafter GBFS) in geopolymer mortar; the workability is increased. The $\text{SiO}_2:\text{Na}_2\text{O}$ ratio of 1.16 achieved the highest early strength after 24 hours; the compressive strength and the tensile and flexural strength of the MK-GBFS geopolymer mortar were also found to be higher than that of ordinary Portland cement mortar and also higher than GBFS geopolymer mortar.

Kumar et al. (2018) observed that the maximum compressive (37.4 MPa after 7 days and 49.2 MPa after 28 days) strength of different combinations of the MK-GBFS geopolymer concrete was obtained with 20% MK and 80% GBFS; additionally, the maximum split tensile strength (3.11 MPa after 7 days and 3.91 MPa after 28 days, consecutively) was obtained with the same combination, namely 20% MK and 80% GBFS.

Borges et al. (2016) concluded that the RHA could be a significant source for the manufacturing of geopolymers when combined with MK; no improvements in mechanical strength were observed when RHA replaced MK up to 30%. When 40% RHA was used in formulations, the mechanical strength dropped to about a half, and any greater addition of RHA caused a strength decrement.

Si et al. (2020) discovered that adding a limited quantity of waste glass powder (less than 10%) to the binder somewhat improved the mechanical properties of geopolymer mortars based on MK. Due to the increased quantity of unreacted glass particles, the high content (20% and more) of waste GP replacement diminished the mechanical properties of the geopolymer mortar.

Using single materials to produce a geopolymer mortar may be associated with certain limitations regarding its use (depending on the material properties). In some situations, the use of a single material to resolve one concern about durability may result in reduced performance due to another (Tosheva and Valtchev, 2005).

The main aim of this study is to obtain a basic understanding of the possible reaction mechanisms that occur when more than two different materials are mixed to produce geopolymer and optimize the design mixes. In this paper, only preliminary results of the experimental studies are shown and discussed, which serve as the basis for the upcoming and more detailed research on the use of more than two different waste materials in the production of geopolymers. Therefore, binary and ternary binder mixtures include two and three different materials, respectively. Using suitably proportioned



4. ASIA PACIFIC INTERNATIONAL CONGRESS ON CONTEMPORARY STUDIES

binary and ternary blends allows one material's effects to compensate for another's inherent weaknesses.

In this study, three different materials (RM, waste GP, and RHA) in addition to MK were used in geopolymer production, which are the byproducts of the manufacturing process. These byproducts are also classified as waste materials. The strength properties (compressive and flexural strength) of the geopolymer mortar produced by composites of metakaolin and three different waste products were investigated.

1. Materials and Methodology

1.1. Materials

The RM used in this study was provided by the Eti Seydişehir (Konya-Turkey) Aluminum Plant. The Kaolin Industrial Mine Company in Izmit supplied the MK used in this work, which had a specific gravity of (2.52 g/cm³); this type of MK is considered to be an effective main material. The waste GP used in this work was provided by the “Mey Kimya” company in Istanbul, the particle size of the waste GP is 30 micron. The RHA used in this work was provided by the “Erdogan” company in Ankara. The Bolu Cement Company provided the GBFS which had specific gravity of (2.88 g/cm³). The river sand used in this project is Izmit's river sand, which had a nominal size of 4.5 mm, a specific gravity of 2.64 and a fineness of 2.36 mm. Table 1 lists the chemical compositions of the used materials.

The alkaline chemicals used as activators were blends of sodium silicate (SiO₂ = 27%, Na₂O = 8.2% and H₂O = 64.8%, specific gravity= 1.32) and 32% vol. NaOH solution (12 M) flakes. The activator solutions were sourced from the AS Kimya company in Istanbul. The chemical compositions of these materials were provided by the manufacturing company.

Table 1. Chemical Composition of the Used Materials*

Compound (% wt.)	RM	MK	GP	RHA	GBFS
SiO ₂	12.6	51.52	69.42	92.33	40.55
Al ₂ O ₃	14.8	44.53	1.09	0.18	12.83
Fe ₂ O ₃	39.61	0.48	0.48	0.17	1.1
CaO	9.23	0.02	8.27	0.02	35.58
K ₂ O	0.85	0.51	0	0	0.68
Na ₂ O	8.8	0.24	12.31	0.29	0.79
MgO	1.75	0.16	4.25	0	5.87
TiO ₂	8.13	0.55	0	0	0.75

*The chemical compositions have been provided by the manufacturing companies mentioned above

2.2 Methodology

2.2.1. Introduction

After the mixing process, 50mm × 50mm × 50mm cubes and 40 × 40 × 160 prisms were cast for compressive strength and flexural strength tests, respectively. After casting in the molds, the specimens were dried at (25°) for 24 hours, then heated in an oven at 80° for 48 hours and finally cured at room temperature until the test dates.



4. ASIA PACIFIC INTERNATIONAL CONGRESS ON CONTEMPORARY STUDIES

After 3, 7 and 28 days of curing using 50 mm cubes, the compressive strength test was conducted where the test procedure was performed in accordance with ASTM C 109. The flexural strength test was also carried out after 3, 7 and 28 curing days using the prismatic samples according to the flexural test procedure as mentioned in ASTM C 348.

2.2.2. Mix Design

The activator solution to binder ratio was 1 by weight, the river sand to binder ratio was 2.5 for all mixes and the sodium silicate to sodium hydroxide ratio was 2 for all mixes. The mixing proportions of composites are shown in Table 2.

Table 2 Mixing proportions of Manufactured Geopolymer Composites (in grams)

Binder	River Sand	GBFS	Activator Solution	
			NaOH (12 M)	Na ₂ SiO ₃
450	1125	60	150	300

In this paper, the strength properties of geopolymer mortar specimens containing three by-products (RM, GP and RHA) in addition to MK are investigated in binary (Mixes 1 to 6) and ternary (Mixes 7 to 22) combinations, based on the following assumptions:

- RM must be included in all ternary binders (minimum 10%) due to the availability of RM as a waste material in Turkey
- The maximum content of each material is 50% of either binary or ternary binders in order to investigate the synthesis effects of the materials together.
- The maximum solution activator to binder ratio is 1 to be practical. If more than this ratio of activator solution is included, it will be expensive and impractical; therefore the combination would be neglected. For instance; mixes containing RHA need more solution in order to be workable otherwise they cannot be cast.
- The sand river to binder ratio is fixed at 2.5 for all combinations.
- The sodium hydroxide that used with sodium silicate to form the activator solution has been prepared in a fixed molarity of 12M for all combinations then the effects of 10 and 14 on the best 5 combinations have been investigated.
- The sodium silicate to sodium hydroxide ratio is 2 for all combinations.
- The heating temperature (for all specimens, heat curing has been conducted for 2 days for all specimens before room temperature curing) in the oven during the first 48 hours is 80 °C.
- The river sand used for all mixes was sieved by using sieve number 4 (size 4.75 mm).

The first six mixes only included two combinations of materials used at a 50-50% ratio. Furthermore, the rest of the specimens (7-22) included various combinations of materials at various proportions.

In Table 3, the mix proportions of binary blended specimens are provided. Subsequently, in Table 4, the mix proportions of specimens' composed three different binders are provided.



4. ASIA PACIFIC INTERNATIONAL CONGRESS ON CONTEMPORARY STUDIES

The activator solution was prepared by mixing sodium hydroxide and sodium silicate. The sodium hydroxide was prepared at 12 M by dissolving 480 grams of solid sodium hydroxide into one liter of pure water and after 24 hours, the activator solution was ready to be added to other materials. An electrical mixer was used to dissolve all the aluminosilicate materials particles by the activator solution before adding the river sand and finally casting the mortar into the molds.

Table 3 The Mix Proportions of Binary Blended Specimens (in grams)

Specimen	Combination	RM	GP	RHA	MK	GBFS	River Sand	Activator Solution
50RM50GP	50% RM+ 50% GP	225	225	0	0	60	1125	450
50RM50RHA	50% RM+ 50% RHA	225	0	225	0	60	1125	> 450
50RM50MK	50% RM+50% MK	225	0	0	225	60	1125	450
50MK50GP	50% MK+ 50% GP	0	225	0	225	60	1125	450
50MK50RHA	50% MK+ 50% RHA	0	0	225	225	60	1125	> 450
50GP50RHA	50% GP+ 50% RHA	0	225	225	0	60	1125	> 450

Table 4 The Mix Proportions of Ternary Blended composites (in grams)

Specimen	Combination	RM	GP	RHA	GBFS	River Sand	Activator Solution
50RM40GP10RHA	50% RM+ 40% GP + 10% RHA	225	180	45	60	1125	450
50RM30GP20RHA	50% RM+ 30% GP + 20% RHA	225	135	90	60	1125	450
50RM20GP30RHA	50% RM+ 20% GP + 30% RHA	225	90	135	60	1125	450
50RM10GP40RHA	50% RM+ 10% GP + 40% RHA	225	45	180	60	1125	450
50MK40RM10RHA	50% MK+40% RM+10% RHA	225	180	45	60	1125	450
50MK30RM20RHA	50% MK+30% RM+20% RHA	225	135	90	60	1125	450
50MK20RM30RHA	50% MK+20% RM+30% RHA	225	90	135	60	1125	450
50MK10RM40RHA	50% MK+10% RM+40% RHA	225	45	180	60	1125	450
50MK40RM10GP	50% MK+40% RM+10% GP	225	180	45	60	1125	450
50MK30RM20GP	50% MK+30% RM+20% GP	225	135	90	60	1125	450
50MK20RM30GP	50% MK+20% RM+30% GP	225	90	135	60	1125	450
50MK10RM40GP	50% MK+10% RM+40% GP	225	45	180	60	1125	450
50GP40MK10RM	50% GP+40% MK+10% RM	225	180	45	60	1125	450
50GP30MK20RM	50% GP+30% MK+20% RM	225	135	90	60	1125	450
50GP20MK30RM	50% GP+20% MK+30% RM	225	90	135	60	1125	450
50GP10MK40RM	50% GP+10% MK+40% RM	225	45	180	60	1125	450

2. Results

The compressive and flexural strength test results of the 22 trial mixes prepared are represented in Sections 3.1 and 3.2, respectively.



4. ASIA PACIFIC INTERNATIONAL CONGRESS ON CONTEMPORARY STUDIES

3.1 Compressive Strength Tests Results

In this section, the compressive strength of all combinations shown in Table 3 and 4 are investigated; however, it is important to mention that combinations that include RHA needs much more chemical solutions (activator) to be workable in comparison to other combinations. As mentioned earlier in this paper, increasing the amount of chemical solutions increases the cost of production. Therefore, RHA has been neglected in later stages due to this reason.

Figures 1 shows that amongst the first 6 specimens; (50% RM+50% MK) and (50% MK+ 50% GP) have maximum compressive strength at 3, 7 and 28 days, (62.39, 46.6 and 44.45 MPa) and (42.57, 54.55 and 46.98 MPa), respectively. These results indicate that further investigation should be undertaken on the binary combinations of these three materials (RM, MK, and waste GP).

In specimens of (RM+GP+RHA) composites, it is shown in Figure 1 that the compressive strength of the mixes increased according to the increasing rice husk ash content up to an optimum percentage of 30%, after which it began to decrease. More previously mentioned, rice husk ash needs more chemical solution than the optimum target which is 1 (activator solution: binder), so rice husk ash has been neglected in later stages.

In specimens of (MK+RM+RHA) composites, it shown in Figure 1 that increasing the rice husk ash content affects the strength properties negatively. It is also shown that the maximum compressive strength for specimen (50MK40RM10RHA) was at 7 days and it decreased at 28 days, which is likely due to the slow chemical reactions between these different materials.

In specimens of (MK+RM+GP) composites, the results shown in the figure 1 present reasonable strength properties of all specimens consist of ternary binders (MK, RM and waste GP) compared to other specimens, the maximum compressive strength (44.01 MPa) has been obtained at 28 days for the specimen (50MK40RM10GP) which contain just 10% of waste glass powder.

In specimens of (GP+MK+RM) composites, the results in figures 1 shows that the maximum compressive strength of the ternary binder combinations consisted of waste GP, MK and RM obtained by the (50GP40MK10RM), and it is decreased with increasing RM content. Additionally, the results show that compressive strength decreased with time for all four combinations.

3.2 Flexural Strength Results

The flexural strength test results of the 22 trial mixes prepared are examined in this section. Figure 1 shows that in the first 6 specimens (binary composites), specimens (50% RM+50% MK) and (50% MK+ 50% GP) have maximum flexural strength at 3, 7 and 28 days with (6.628, 6.824 and 9.21 MPa) and (10.87, 10.62 and 9.19 MPa), respectively. These results indicate that further investigations should be undertaken on the binary combinations of these three materials (RM, MK and waste GP).

In specimens of (RM+GP+RHA) composites, the maximum flexural strength was obtained with an optimum percentage of rice husk ash of 20%, and decreased for higher percentages (30% and 40%). These results show that in addition to the high cost of chemical solutions the ternary combinations of these materials do not acceptable strength properties. In specimens of (MK+RM+RHA) composites, it was also shown that increasing the rice husk ash content affects the strength properties negatively in addition to the previously mentioned drawback regarding the use of more chemical solution to make it workable. It also been shown that the flexural strength for combination (50MK40RM10RHA) reached



4. ASIA PACIFIC INTERNATIONAL CONGRESS ON CONTEMPORARY STUDIES

a maximum at 28 days. In specimens of (MK+RM+GP) composites, all flexural strength results for the 4 combinations are reasonable, as shown in Figure 2. The maximum flexural strength of 11.98 MPa was obtained at 28 days for the (50MK30RM20GP) specimen, which contains just 20% of waste glass powder. In specimens of (GP+MK+RM) composites, the results in figure 2 show that the maximum flexural strength of the ternary binders combinations consisting of waste GP, MK and RM was obtained from the (50GP40MK10RM) specimen, and it is decreased with increasing red mud content.



4. ASIA PACIFIC INTERNATIONAL CONGRESS ON CONTEMPORARY STUDIES

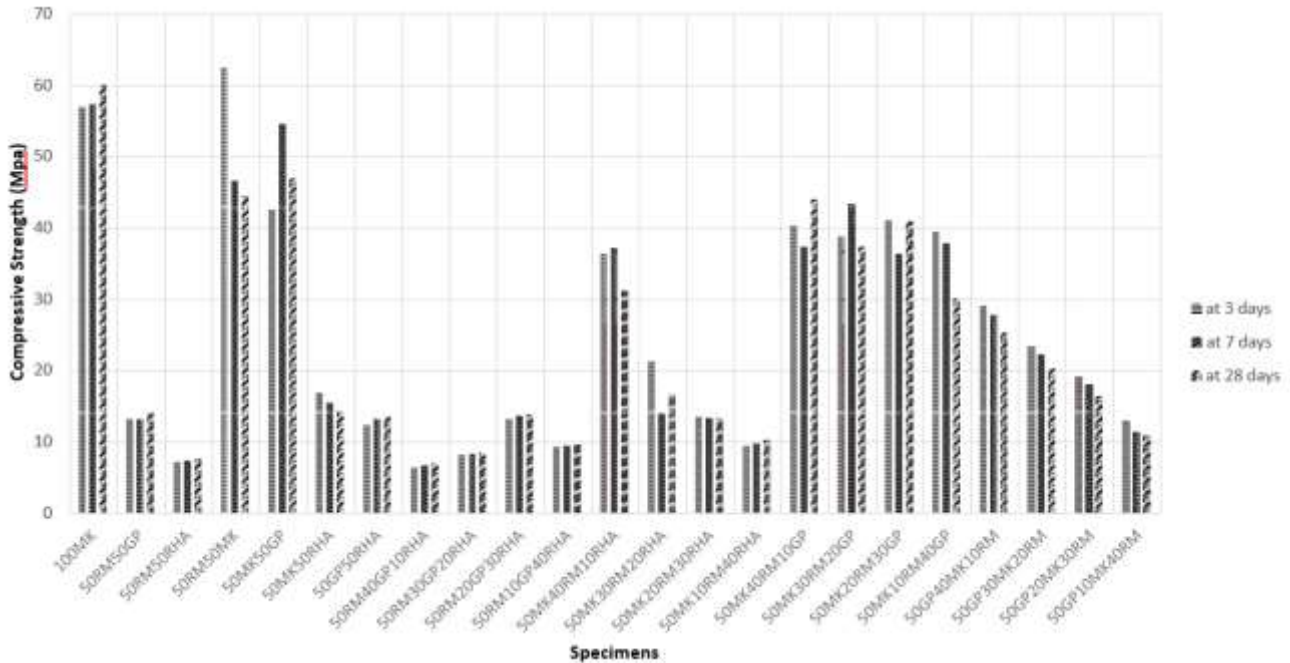


Figure 1 Compressive Strengths of mixes

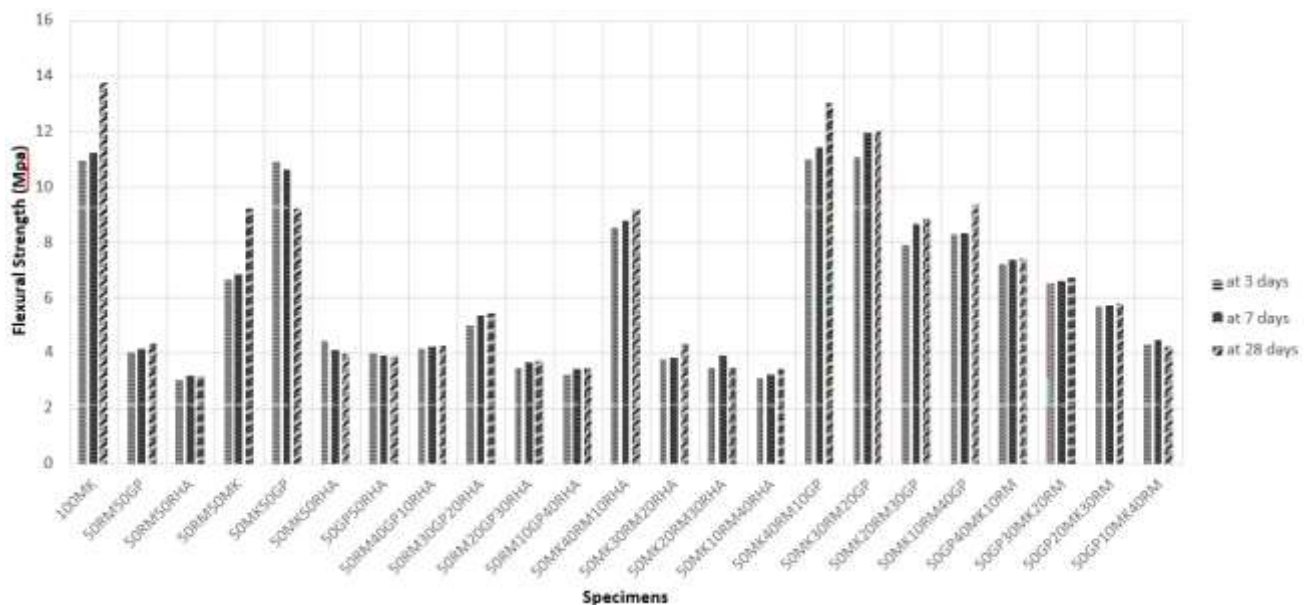


Figure 2 Flexural strengths of blended composites

3.3 The Effects of Molarity on the Compressive Strength

After deciding which composites have reasonable compressive strength and flexural strength results from the previous section, it is observed that the molarity affects the strength properties of geopolymer mortar significantly. The effects depend on the properties of the binder Materials; hence, the effects of



4. ASIA PACIFIC INTERNATIONAL CONGRESS ON CONTEMPORARY STUDIES

changing the molarity of the sodium hydroxide on the compressive strength at 28 days has been investigated by three different molarities: 10, 12 and 14. The results are shown in Table 5:

Table 5 Compressive strength at different molarities

Specimen Formulation	Compressive Strength at 28 days (MPa)		
	10 mol	12 mol	14 mol
50%MK+40%RM+10%GP	31.42	44.01	35.62
50% MK+30%RM+20%GP	28.91	37.25	31.23
50% MK+20%RM+30%GP	24.52	40.93	34.81
50% RM+50% MK	28.21	44.45	33.94
50% MK+ 50% GP	27.39	46.98	37.78

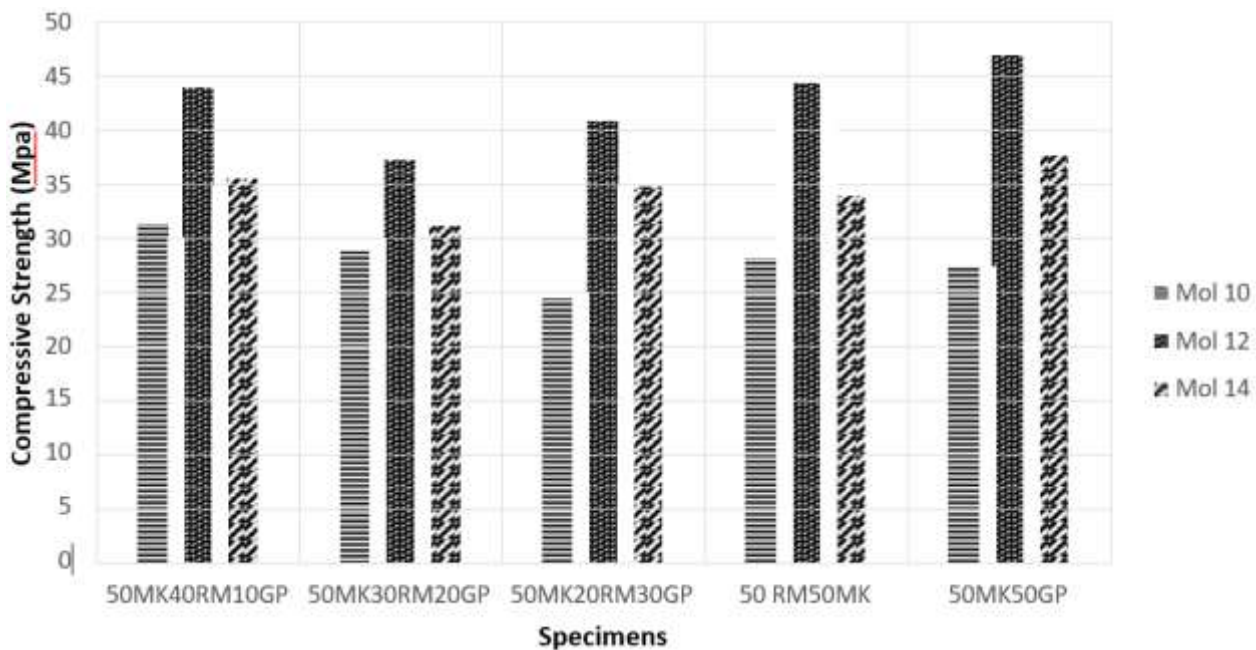


Figure 3 The Molarity effects on compressive strength

3. Discussions

Compressive strength results of specimens incorporated with RM, MK, RHA and GP in different proportions are plotted in Figure 4. All results are compared with 100MK which is the control specimen. When binaries (two combinations) are examined, it can be stated that; **RM creates** an effective chemical combination with MK but not with GP and RHA. Because, % reduction in compressive strength values of 50RM50MK, 50RM50GP, 50RM50RHA specimens, relative to 100MK are; 26%, 76% and 87%, respectively.



4. ASIA PACIFIC INTERNATIONAL CONGRESS ON CONTEMPORARY STUDIES

On the other hand, **MK** is good both with GP and RM but not good with RHA. Here, % reduction in compressive strength values of 50MK50GP, 50MK50RM 50MK50RHA, relative to control (100MK) are; 22%, 26% and 76% respectively. Compatibility of MK with GP is slightly better than that of RM.

When RHA combination with MK (50MK50RHA) is compared with that of RHA combination with RM (50RM50RHA), it is found that the former performs better, since 50RM50RHA compressive strength is 87% less than 100MK and for the latter this value is only 76%.

GP creates effective combination with MK, but not good either with RM and RHA. 50GP50MK is only 22% less than 100MK, whereas 50GP50RM and 50GP50RHA are 76% and 78% less than that of control, 100MK, respectively.

In the ternary combinations, it is more complicated to make a comment on compressive strength results. First; **RM, GP and RHA** (50%RM and 50%(GP+RHA)) combinations are examined. As it is mentioned above, RM creates an effective chemical combination only with MK (26% decrease in \square_c), but not with GP (76% decrease in \square_c), and RHA (87% decrease in \square_c). Here

\square_c is mainly controlled by GP and increased with decreased amount (from 40 to 10) of GP and reached to a maximum at 20% GP (50RM20GP30RHA), then decreased again at 10% GP.

It was observed that when RM kept constant at 50% and the ratios of GP and RHA was varied, the results showed that when GP reduced down to 20% and RHA increases up to 30 an increment was observed in the compressive strength development whereas, at 40%RHA addition with the decrease of GP down to 10% a reduction of strength development was observed. This proves the fact that the optimum level where the strength development is continuously happening would be 50RM20GP30RHA which is accepted as the optimum ratio.

Second; **MK, RM and RHA** (50%MK and 50%(RM+RHA)) combinations are examined. As is mentioned above, MK is compatible with RM but not with RHA. Therefore with increased RHA (from 10 to 40) and decreased RM (from 40 to 10); \square_c was reduced. Here, it is important to note that; there is a sharp decrease (nearly half) in \square_c , when RHA content increased from 10% to 20%. After that, decrement in \square_c continued linearly for 20, 30 and 40% RHA contents.

Additionally, when RM and RHA materials incorporated into 50% MK several ternary mix designs were proposed. Accordingly, when MK kept constant at 50% and RM reduced from 40% down to 10% in parallel to the increment in RHA ratio from 10% to 40%; a linear change was observed amongst the mix design by means of strength development. There is a linear reduction in compressive strength in parallel to the increase in curing age from 3 days to 28 days. This shows that any ratios lower than 40% for RM would detrimentally influence the strength development even though there is an increase in the RHA content from 10% to 40%. So, as it was proved in first stage of the trials with binary mix designs MK and RM performs really well in compressive strength individually but also when they get together at reasonable ratios. (50:50 would be optimum level where they reached the max values, on the other). On the other hand, additional 10%RHA incorporation would cause approximately 50% reduction in the strength development.

Third; **MK, RM and GP** (50%MK and 50%(RM+GP)) combinations are examined. As is mentioned above MK is compatible both with RM and GP. Therefore \square_c results of all combinations (RM from 40 to 10 and GP from 10 to 40) are similar and close to 50MK50RM and 50MK50GP \square_c results.

Forth; **GP, MK and RM** (50%GP and 50%(MK+RM)) combinations are examined. As is mentioned above GP is compatible with MK but not with RM. Therefore \square_c results of GP, MK and RM combinations, decreased linearly; with decreased MK (from 40 to 10), and increased RM (from 10 to 40). \square_c result of 50GP40MK10RM, which is the best one in this group is found to be 58% less than that



4. ASIA PACIFIC INTERNATIONAL CONGRESS ON CONTEMPORARY STUDIES

of control (100MK), and % decrement for 50GP10MK40RM specimen which is the worst one is 82. As known performance of GP, RM and MK on strength development when three of them get together it is very difficult to evaluate which one performs better or worse on each other. As it can be seen from the results as well it is very difficult to say whether there is a linear or nonlinear increment or decrement on strength development out of these combinations which are composed of MK:RM:GP at different ratios (MK kept constant at 50%). However, when

the amount of MK varies and GP ratio kept constant even out of the combinations of these three materials it is very easy to comment on their performance. When the ratio of GP kept constant at 50% and the value of MK reduced from 40% to 10% and RM increased from 10% to 40% it is obvious that there is linear decrease in the strength development. As a result, out of these trial mixtures it can be concluded that MK has a very obvious effect on the mechanical properties of the mortars produced and perform really well compared to any other materials mentioned above. The decrease in RM or GP would not affect the strength development when the MK is kept constant. However, when the GP ratio kept constant and MK and RM values reduced proportionally then a very obvious deduction in the strength development was observed regardless of the curing age.

The highest first three of 28-days σ_c : 50MK50GP (22% less than 100MK), 50MK50RM (26% less than 100MK), 50MK40RM10GP (27% less than 100MK). Therefore using mainly MK and GP and RM in geopolymer concrete production is appropriate.

At the end, it can be stated that; incorporation of MK at different % tags in mix combinations considerably influences the compressive strength development. MK behaves quite promising compared to any other material in strength development. This is probably due to the high reactivity of MK. MK possesses high reactivity with calcium hydroxide which accelerates the cement hydration. RM has a very fine-particle structure which is a promising element for geopolymer mortar. A combination of both materials, i.e. RM and MK enhance the strength development of the mix matrix regardless of the curing age.

Interestingly the results achieved showed that GP performs way better when mixed with MK rather than RM except at 3 days curing age. As explained earlier this is mostly due to the early strength development potential of RM. Out of all mix designs studied, it was observed that RHA works with MK than all other materials. In addition to this, the results proved that RHA works better with GP than RM. Therefore, out of these results better performances by means of strength development with the combination of GP and MK is inevitable at 50:50 mix ratio.

MK has pozzolanic properties. MK possesses a high reactivity with calcium hydroxide having the ability to accelerate cement hydration. Since current concrete structures present higher permeability levels that allow aggressive elements to enter, leading corrosion problem, using pozzolanic admixtures not only reduce carbon dioxide emissions but also allow structures with longer service life, thus lowering their environmental impact. Therefore, use of metakaolin as the main ingredient of a geopolymer mortar and concrete would be quite

Advantageous by means of reaching better mechanical properties addition to better durability and most importantly would help to produce a very environmental friendly concrete which has little impact on environment compared to cement concrete. Results show that concrete incorporating metakaolin had higher compressive strength and metakaolin enhanced durability of concretes and reduced the chloride diffusion. Metakaolin based geopolymers would reach better performance in case of strength parameters such as compressive, flexural and split tensile strength.



4. ASIA PACIFIC INTERNATIONAL CONGRESS ON CONTEMPORARY STUDIES

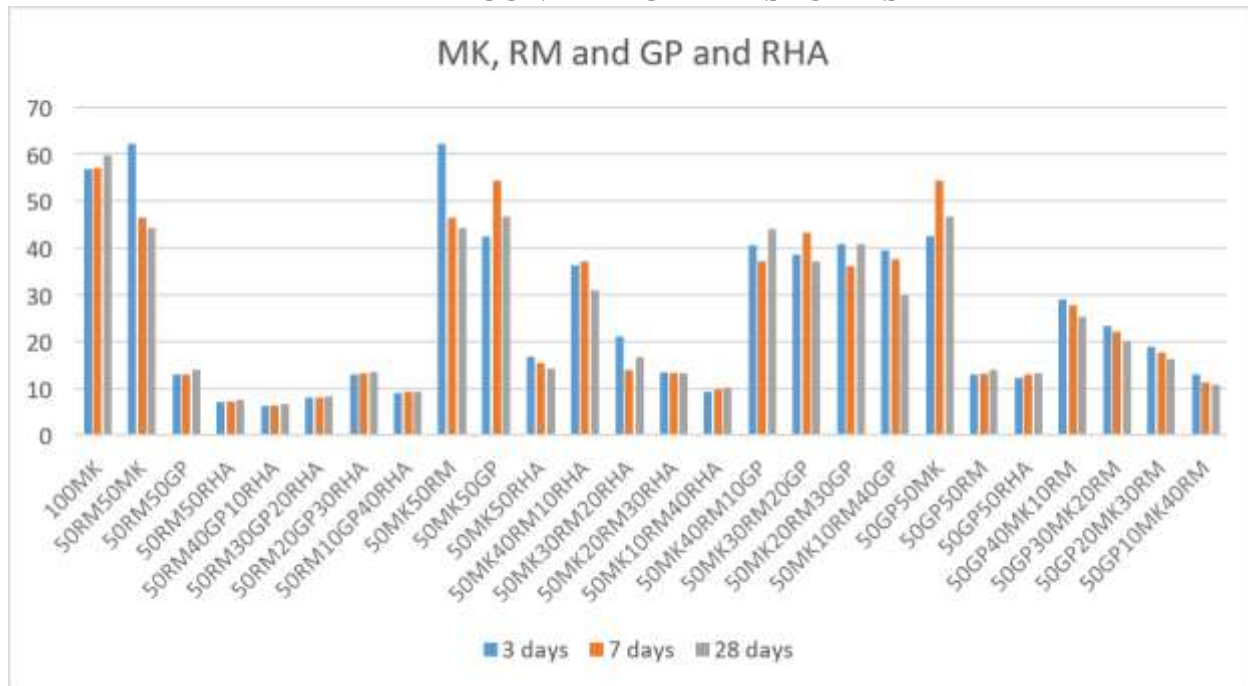


Figure 4. Compressive strength results of specimens incorporated with RM, MK, RHA and GP in different proportions

4. Conclusions

Geopolymer mortar could represent a reasonable alternative for cement mortar, and it will be more valuable and sustainable if waste materials are used due to the high costs of waste disposal and the negative effects of landfills on the environment. Therefore, it can be concluded that:

- Early strength could be achieved by curing at elevated temperatures for 48 hours at (60° -80°) and the strength development is affected by chemical reactions between the binder components
- Geopolymer mortar could be produced by using 50% waste materials and it provides reasonable strength properties
- RM creates an effective chemical combination with MK but not with GP and RHA.
- MK is good both with GP and RM but not good with RHA. Compatibility of MK with GP is slightly better than that of RM. 50% MK and different combinations of GP and RM give remarkable compressive strength and flexural strength.
- GP creates effective combination with MK, but not with RM and RHA. 50GP50MK is only 22% less than 100MK, but 50GP50RM and 50GP50RHA are 76% and 78% less than that of control, 100MK, respectively.
- Incorporation of MK, RM and GP at different percentages in mix combinations, enhance the strength development of the mix regardless of the curing age.
- SiO₂/Al₂O₃ ratio and SiO₂ content affect the σ_c value. As far as SiO₂/Al₂O₃ ratio is below 3, higher amount SiO₂ positively affect σ_c value. Using an alkaline activator solution consisting of a mixture of sodium silicate and sodium hydroxide solution increases the dissolution of these different waste materials and improves the mechanical properties.
- For different waste materials, the activator solution to binder mass ratio has noticeable effects



4. ASIA PACIFIC INTERNATIONAL CONGRESS ON CONTEMPORARY STUDIES

on the followability of the geopolymer mortar; the ratio 1:1 achieves acceptable workability for most of the combinations.

- Rice husk ash needs significantly more chemical solution to react with other materials and to be workable, so it is not practical to use it even in low percentages due to the cost of the chemical solution.
- The molarity of sodium hydroxide affects the mechanical properties of the geopolymer mortar significantly; the molarity 12 gives the highest compressive strength compared to the molarities 10 and 14.
- The effects of changing the river sand ratio and the addition of inorganic fibers on the performance of these composites will be investigated in further papers as a future study.

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