Optimization of Alkali Activator Solution to Enhance the Performance of Roller Compacted Concrete for Pavements

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ABSTRACT

Due to the recent inclination towards reducing greenhouse gases (GHG), less energy-intensive construction, and reuse of waste and secondary materials, this study focuses on maximizing the mechanical performance of environment-friendly roller compacted concrete for pavements (RCCP). Alkali-activated roller compacted concrete for pavements (AA-RCCP) is prepared in this study by alkali activation of ground granulated blast furnace slag (GGBFS) and fly ash (FA). The use of an alkali activator solution with varying density and viscosity for alkali activation further complicates this research since roller-compacted concrete (RCC) is extremely sensitive to moisture. Five distinctive molarities of NaOH and three varying proportions of Na_2SiO_3 for each morality were used to develop 15 mix designs that were tested to maximize the performance of AA-RCCP. Fresh properties such as optimum moisture content (OMC) and maximum dry density (MDD) were first evaluated for each mix formulation. The effect of variation in alkali activator solution on hardened properties like compressive strength, flexural strength, and split tensile were studied. In addition, the effect of varying alkali activator dosages, dry density, void ratio, delay in compaction, and curing age on compressive strength was also evaluated. Based on the findings of the tests conducted in this study, AA-RCCP can be considered an environment-friendly alternative option for the construction of pavement and other facilities.

Keywords: Alkali Activated Roller compacted concrete (AA-RCC), Roller Compacted Concrete (RCC), Ground granulated Blast Furnace Slag (GGBFS), Fly ash, Sustainable Pavements.

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List of Abbreviations

RCC	Roller Compacted Concrete
RCCP	Roller Compacted Concrete for Pavements
OPC-RCC	OPC based Roller Compacted Concrete
OPC	Ordinary Portland Cement
AA-RCCP	Alkali Activated Roller Compacted Concrete for pavements
FA	Fly Ash
GGBFS	Ground Granulated Blast Furnace Slag
AAC	Alkali Activated Concrete
LS	Lime Stone
CWA	Coal Waste Ash
CWP	Coal Waste Powder
GPC	Geopolymer Concrete
AA	Alkali Activator
OMC	Optimum Moisture Content
MDD	Maximum Dry Density
SCMs	Supplementary Cementitious Material
XRF	X-Ray Fluorescence
AASC	Alkali Activated Slag Concrete
OPCC	Ordinary Portland Cement Concrete
NMAS	Nominal Maximum Aggregate Size
ASTM	American Standard for Testing Materials
ACI	American Concrete Institution
M	Molarity of NaOH
R	$NaOH/Na_2SiO_3$

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Chapter 1

1 Introduction

1.1 Background

Roller compacted concrete (RCC) is well-known among all varieties of concrete due to its ability to derive strength and durability from both compaction effort and the hydration of cement, despite a substantially lower cement content than conventional concrete. Historically, RCC was used for the construction of massive earth dams, but a later trend of increasing use of roller compacted concrete pavement (RCCP) technology was observed for the construction of pavements, shipping yards, loading docks, truck terminals, bulk storage facilities, and military facilities [1, 2]. Due to the association of factors such as high energy consumption and carbon emissions with the production of cement, numerous attempts have been made to make RCC more durable and eco-friendly. The cement manufacturing industry is the second-greatest producer of carbon dioxide [3]. When cement is produced using a wet processing plant and a plant with pre-calcination, 1.1 and 0.8 metric tons of carbon dioxide are produced, respectively [4]. One ton of cement production requires six million BTU of energy, making it the third most energy-intensive process after steel and aluminum [5]. Cement production also utilizes natural resources; one ton of cement requires 1.6 tons of raw materials [5]. In order to reduce carbon emissions, cement is frequently replaced with various raw materials and by-products. However, due to the exponential rise in demand for cement, researchers have developed a technology called alkali activation that can completely replace cement in concrete. In alkali-activated concrete (AAC) technology, aluminum-silicate-rich materials such as fly ash, GGBFS, and rice husk ash are activated in the presence of strong alkalis to form a network of three-dimensional polymerized molecular chains that are responsible for the material's strength. Complete substitution of cement with alkali activation technology can reduce carbon emissions by nine times compared to cement-based concrete [6].

1.2 Problem Statement

Optimum moisture content (OMC) and maximum dry density (MDD) fluctuate with varying cementitious dosages and gradations of fine and coarse aggregates; thereby, OMC and MDD should be first calculated for maximizing the mechanical properties of roller compacted concrete for pavements (RCCP) [1, 2, 7]. RCCP is very sensitive to moisture content, and the integration of RCCP with alkali activation technology makes it more complex. The viscosity and density of the alkali activator change with the variation of the molarity of sodium hydroxide (NaOH) and the amount of sodium silicate (Na_2SiO_3) in the alkali activator solution. Due to variations in the density and viscosity of the alkali activator solution, OMC and MDD vary for each mix design. The combination of fly ash (FA) and ground granulated blast furnace slag (GBBFS) makes this study more complex, as fly ash is properly activated at higher molarities of NaOH up to 14M [8], whereas GBBFS can be activated at relatively lower molarities of NaOH [9]. So, for maximizing the performance of alkali-activated roller compacted concrete for pavements (RCCP), optimization of the alkali activator solution is needed while maintaining optimum moisture content and maximum dry density.

1.3 Research Objectives

The objective of this study is to improve the mechanical properties of environmentally friendly roller compacted concrete for pavements (RCCP) in accordance with the goal of mitigating greenhouse gas emissions and advancing sustainable construction practices. The primary objective of this study is to investigate the application of alkali-activated roller compacted concrete for pavements (AA-RCCP), which involves the activation of ground granulated blast furnace slag (GGBFS) and fly ash (FA) using alkali activators. For optimization of alkali activator solution, this study entails the examination of 15 AA-RCCP combinations, wherein the concentrations of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) are varied. The evaluation focuses on the fresh qualities of the mixtures, including the determination of the optimum moisture content (OMC) and maximum dry density (MDD). In addition, this study examines the effects of alkali activator solutions on the mechanical characteristics of hardened materials, namely the compressive, flexural, and split tensile strengths. The investigation additionally examines many variables, including the quantities of alkali activator used, density, void ratio, compaction delay, and curing age, in order to evaluate their impact on the compressive strength.

1.4 Research Significance

In contrast to conventional ordinary Portland cement (OPC) concrete, roller compacted concrete (RCC) offers a notably more sustainable option that demonstrates both economic efficiency and environmental responsibility. Roller compacted concrete (RCC) has several inherent advantages, such as decreased labor demands, elimination of formwork requirements, and reduced expenses, with potential cost reductions of up to 60%. Significantly, the limited amount of ordinary Portland cement (OPC) present in roller-compacted concrete (RCC) plays a crucial role in enhancing its economic viability and reducing its energy requirements. The incorporation of alkali activation technology enhances the environmental sustainability of RCC. It is crucial to acknowledge that the manufacturing of OPC accounts for around 5–7% of world carbon dioxide emissions. In large-scale operations such as the construction of dams and pavements, where a significant amount of ordinary Portland cement (OPC) is used, the consideration of prospective replacements becomes crucial. The implementation of this strategic shift has the potential to generate substantial environmental advantages while simultaneously positively impacting project costs. This represents a progressive advancement towards sustainability.

1.5 Research Scope

Building upon the research objectives, the project's scope is outlined as follows:

- The aim of this study is to optimize the alkali activator solution in order to enhance the performance of alkali activated roller compacted concrete for pavement applications (AA-RCCP).
- The objective of this study is to investigate the impact of the molarity of NaOH and the ratio of NaOH to Na_2SiO_3 in the alkali activator solution on the fresh properties, such as optimum moisture content (OMC) and maximum dry density (MDD), as well as the mechanical properties of alkali activated roller compacted concrete for pavement (AA-RCCP).
- To investigate the impact on strength due to the deviation of alkali activator content from OMC.
- The study assessed the impact of curing age and compaction delay on the compressive strength of AA-RCCP.

1.6 Thesis organization

The entirety of the thesis is organized into five distinct chapters. The first chapter of this thesis provides an overview of roller compacted concrete (RCC) and clarifies the problem statement, as well as outlining the research area. The second chapter focuses on a comprehensive examination of the literature covering the technologies of Roller-Compacted Concrete (RCC) and alkali-activated concrete (AAC). The third chapter of this thesis provides an extensive review of the methodology, materials, and testing methods employed in the study. The fourth chapter of this study covers the findings obtained from the conducted tests and provides a comprehensive discussion of these results. The fifth chapter provides a comprehensive summary of the research findings and offers some recommendations to improve the study. The last section of this thesis is about references, in which all the references that were used to support this research are cited.

Chapter 2

2 Literature Review

2.1 Studies on OPC based Roller Compacted Concrete

Numerous attempts have been undertaken in the past to enhance the cost-effectiveness and environmental sustainability of RCC. Several researchers have attempted to substitute ordinary Portland cement (OPC) with supplemental cementitious materials (SCMs), while others have explored the replacement of aggregate with recycled aggregate and shredded rubber aggregates. Hazaree et al. investigated the mechanical properties and freeze-thaw resistance of RCC by varying the cementitious material content of RCC from 100 to 450 kg/m^3 and concluded that 225±25 Kg/m^3 is the optimum range for producing RCC [10]. The study conducted by Nili and Zaheri [11] investigated the effects of fly ash and nano-silica on the fresh and mechanical properties of RCCP mixtures. The consistency of fresh concrete is improved by replacing 8 to 20 percent of the cement with pozzolans. The substitution of silica fume led to a notable enhancement in compressive strength, freeze-thaw durability, and resistance to salt-scaling. Based on the findings of Courard et al. [12], the substitution of coarse natural aggregate with road recycled aggregates in roller-compacted concrete (RCC) results in the preservation of its solid compactness, albeit accompanied by a reduction in its compressive strength. The study found that changes in cementitious material did not significantly impact the density of the solid but had a significant influence on the compressive strength. Given the susceptibility of compressive strength to fluctuations in the dosage of cementitious materials, it is advisable to adhere to a minimum dosage of 200 kg/m^3. In a study conducted by Madhkhan et al. [13], it was seen that the compressive strength of RCC pavements exhibited a decrease after a period of 28 days when pozzolans were utilized as a substitute for cement at replacement levels of 30%, 40%, and 50%. However, it was noted that the compressive strength showed a rise after a duration of 90 days. Additionally, the researchers conducted an analysis on the impact of polypropylene and steel fibers in reinforced concrete composites (RCC). Their findings indicated that the inclusion of steel fibers led to enhanced compressive strength and toughness, while neither type of fiber contributed to an increase in the modulus of rupture. In a study conducted by Meddah et al. [14], an investigation was carried out to assess the effects of incorporating rubber as a substitute for coarse aggregate at different proportions. The findings of the study indicated that as the rubber content increased, both the density and compressive strength exhibited a drop. The utilization of rubber as a substitute for natural aggregates resulted in several benefits, including reduced compaction time, enhanced resistivity, and improved ductility. In their research, Rao et al. [15] conducted an investigation where they substituted ordinary Portland cement (OPC) with ground granulated blast furnace slag (GGBFS) in roller-compacted concrete (RCC) at various replacement levels, ranging from 10% to 60%. The researchers then proceeded to compare the outcomes of these combinations with those of RCC control mixtures. The researchers reached the determination that the compressive strength exhibits enhancement up to a replacement level of 50%, above which it begins to deteriorate. A strong connection was also noted between compressive strength, abrasion resistance, split tensile strength, and flexural strength. The impact of manufactured sand and fly ash on roller-compacted concrete (RCC) was investigated by Rao et al. [16]. The research revealed that the utilization of manufactured sand leads to improved abrasion resistance in all mixtures when compared to river sand. With the goal to investigate the impact of fly ash, the cement content varied from 0% to 60%. The findings revealed an adverse relationship between the proportion of fly ash in the mixtures and both compressive strength and abrasion resistance. Moreover, a clear relationship was identified between the resistance to abrasion and the compressive strength of Roller-Compacted Concrete (RCC). Hesami et al. [17] investigated the utilization of coal waste powder (CWP), coal waste ash (CWA), and limestone powder (LS) as potential substitutes for cement in roller-compacted concrete pavement (RCCP) at varying proportions of 5%, 10%, and 20%. In the instances of CWP and CWA, it was observed that the hardened properties, including compressive strength, flexural strength, and split tensile strength, were comparable to the control mixture when the replacement amount was set at 5%. The mechanical performance of Roller-Compacted Concrete Pavement (RCCP) exhibits a decline when the replacement level of cement is elevated. It has been determined that a combination of CWA and LS provides a more favorable option for substituting cement in RCCP. Fakhri and Saberi [18] conducted a study with the objective of improving performance and mitigating carbon emissions by the substitution of rubber waste particles for sand and silica fume for cement. The researchers conducted an experiment wherein they substituted sand with rubber waste in several proportions, ranging from 0% to 35% with a 5% increment. Through their investigation, it was shown that the compressive strength of RCCP (Roller Compacted Concrete for Pavement) exhibited enhancement at replacement levels of 5%

and 10% when compared to the control sample containing natural sand. A comparable enhancement in strength was reported when 10% of the cement was replaced with silica fume.

2.2 Alkali activated concrete

Alkali activation technique, in contrast to Ordinary Portland Cement (OPC) concrete, is a relatively recent development. This method entails the activation of aluminum silicate-rich materials by the utilization of potent alkali solutions, frequently referred to as alkali activators. In their study, Hadi et al. [19] employed a mixture of 14M sodium hydroxide solution and sodium silicate solution, with a sodium silicate to sodium hydroxide ratio of 2.5, to activate GGBFS. The authors successfully attained a compressive strength of 60.4 MPa during a seven-day period. Furthermore, an investigation was conducted on the substitution of ground granulated blast furnace slag (GGBFS) with fly ash (FA), revealing that the incorporation of fly ash led to an increase in both the initial and final setting times. Furthermore, it was determined that the incorporation of Ground Granulated Blast Furnace Slag (GGBFS) and Fly Ash (FA) presents a feasible alternative for on-site building, as it offers improved workability and obviates the necessity for thermal curing. Nath and Sarker [20] conducted an investigation on the utilization of a combination of ground granulated blast furnace slag (GGBFS) and fly ash (FA) in geopolymer concrete. Their findings revealed that by replacing 30% of GGBFS with FA in fly ash-based geopolymer concrete, it was possible to achieve a compressive strength of up to 55 MPa. The utilization of a sodium hydroxide (NaOH) and sodium silicate solution (Na_2SiO_3) for the activation of ground granulated blast furnace slag (GGBFS) and fly ash (FA) resulted in the observation that an increase in the sodium silicate content led to a reduction in slump, setting time, and compressive strength. The study conducted by Nuaklong et al. [21] found that the incorporation of recycled aggregates (RCA) in fly ash geopolymer concrete resulted in a marginal decrease in both durability and compressive strength, as compared to the usage of limestone aggregates instead of RCA. The researchers conducted experiments with sodium hydroxide solutions with concentrations of 8M, 12M, and 16M. Through their investigation, they concluded that the 12M sodium hydroxide solution exhibited the highest levels of compressive strength and durability, making it the optimum choice. Bernal et al. [22] conducted a comparison between alkali-activated slag concrete (AASC) and ordinary Portland cement concrete (OPCC) in terms of their respective strengths. The researchers achieved this by altering the cementitious concentration at three different levels, namely 300, 400, and 500 kg/m^3. It was observed that the compressive strength of alkali-activated slag concrete

(AASC) exceeded that of ordinary Portland cement concrete (OPCC) at all levels of dosage. Additionally, it was found that the compressive strength exhibited a positive correlation with the amount of slag used.

2.3 Alkali activated roller compacted concrete for pavements (AA-RCCP)

Extensive research has been conducted on the alkali activation of concrete in the context of traditional concrete. However, little efforts have been made to explore this process in the context of Roller-Compacted Concrete Pavement (RCCP) technology. This can be attributed to challenges associated with heat curing, reduced setting time, and the vulnerability of RCC to moisture content. In their study, Bastani and Behfarnia [9] successfully employed alkali activation of slag in the context of reinforced concrete construction (RCC). Their experimental results demonstrated the achievement of a notable compressive strength of 60MPa. Additionally, it was observed that increasing the quantity of sodium hydroxide resulted in an elevation of initial strength, however accompanied by a decline in the rate of long-term strength development. In their pioneering work, Rahman and Khattak [23] employed fly ash-based geopolymer technology in reinforced concrete construction, marking the first instance of totally replacing recycled concrete aggregates (RCA) with natural aggregates. Additionally, it was determined that the compressive strength of sodium hydroxide increased proportionally with its molarity. It has been determined that the increase of the sample's strength can be achieved through subjecting it to a temperature of 60°C for a duration of 48 hours.

Chapter 3

3 Methodology and Materials

3.1 Experimental Program

This study focuses on the development of alkali-activated roller compacted concrete for pavements (AA-RCCP) by the using soil compaction method [7]. The alkali activation of ground granulated blast furnace slag (GGBFS) and fly ash (FA) involved the utilization of a liquid mixture of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). A total of five distinct molarities of sodium hydroxide (NaOH) and three varying dosages of sodium silicate (Na_2SiO_3) were employed for each respective molarity of NaOH. The experimental program has two distinct phases. During the initial stage, the determination of the optimal moisture content (OMC) and maximum dry density (MDD) for each combination of alkali activators was conducted by establishing a relationship between the dose of alkali activators and the dry density. Through analysis of cylindrical specimens, the correlation between compressive strength and the doses of alkali activators is also established. During the subsequent stage of this study, cylindrical samples were produced using the optimal moisture content (OMC) associated with each combination of alkali activators. Figure 2.1 shows the experimental program for this research. Afterwards, an assessment was conducted to determine the mechanical parameters, including compressive strength, flexural strength, and split tensile strength. Furthermore, this study examines the impact of void ratio, density, compaction delay, and curing duration on compressive strength.

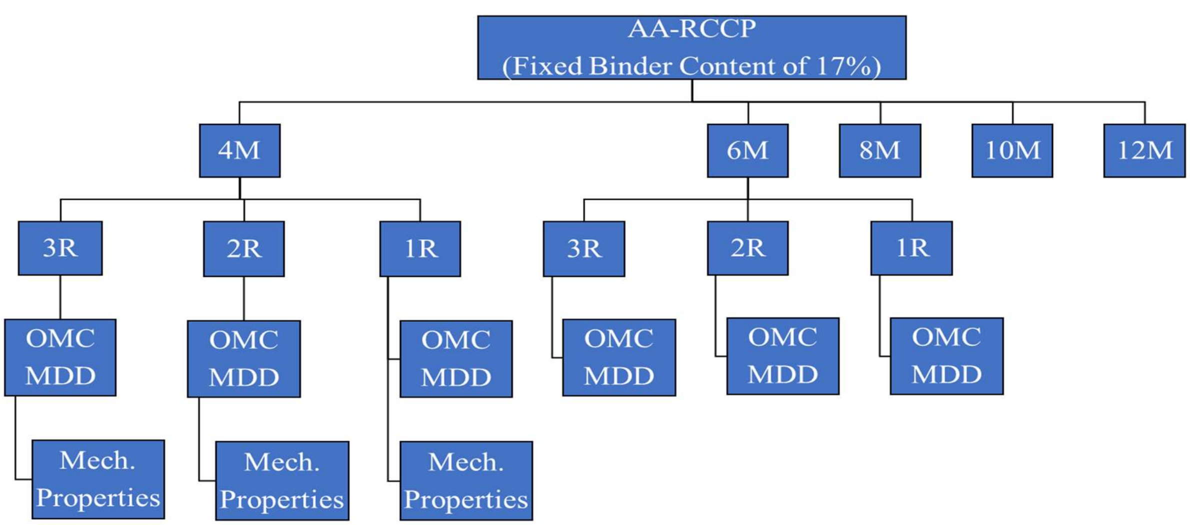


Figure 3.1 Experimental program for optimization of alkali activator solution.

3.2 Materials

3.2.1 Cementitious Materials

The present study involved the utilization of ground granulated blast furnace slag (GGBFS) obtained from Deewan Cement Company, located in Pakistan. Ground Granulated Blast Furnace Slag (GGBFS) exhibits a specific gravity of 2.85 and a fineness, as determined by air permeability, of 6868 cm^2/g. The Port Qasim Power Plant, located in Karachi, Pakistan, supplied Class F fly ash that possessed a specific gravity of 2.25, as per the guidelines outlined in ASTM C618 [24]. Ordinary Portland Cement (OPC) of type-I according to ASTM C-150, with a specific gravity of 3.15 according to ASTM C-188, and with a fineness modulus of 3% according to ASTM C-430 [25] was used in this investigation to produce OPC-based RCC [26, 27]. Table 3.2.1 presents the chemical composition of Ground Granulated Blast Furnace Slag (GGBFS), Fly Ash (FA), and Ordinary Portland Cement (OPC), by performing X-Ray Fluorescence (XRF).

Table 3.2.1 Chemical composition of GGBFS, FA, and OPC.

Properties	Material		
	GGBFS (wt. %)	**Fly Ash (wt. %)**	**OPC (wt. %)**
SiO2	32.7	43.6	20.35
Al2O3	17.8	31.6	4.87
CaO	36.7	3.3	63.5
Fe2O3	4.31	0.6	3.26
MgO	4.45	1.2	2.41
Na2O	0.29	-	-
K2O	0.82	-	0.58
SO_3	0.52	0.34	2.71
Specific Gravity	2.85	2.25	3.15

3.2.2 Alkali Activators

In this study, various dosages of commercially available sodium hydroxide (NaOH) were dissolved in water to achieve the desired molarity. Sodium silicate (Na_2SiO_3) with a specific gravity of 1.53 was supplied by Captain PQ Chemicals, Pakistan. By weight, liquid Na_2SiO_3 contained 46% solids and 54% water. The percentages of SiO2 and Na2O in the solid form of Na_2SiO_3 were 32.04 and 13.96%, respectively.

3.2.3 Aggregates

The study used fine aggregates with a particle size smaller than 4.75 mm as well as coarse aggregates with a nominal maximum aggregate size (NMAS) of 12.5 mm. Based on the guidelines provided in ACI 327R-14 [1], it is recommended to limit the nominal maximum aggregate size (NMAS) to 19 mm in order to avoid segregation. Additionally, if a desirable surface texture is desired, it is advised to consider NMAS ranging from 9.5 mm to 16 mm. Consequently, a significantly smaller NMAS was chosen for the purpose of this study. The coarse and fine aggregates underwent sieve examination using the guidelines outlined in ASTM C136 [28]. The construction of the combined aggregate gradation curve, as depicted in Figure 3.2.3, was accomplished by the analysis of diverse combinations of fine and coarse aggregates. A combination of 40% coarse aggregate (ranging from 4.75 to 12.5 mm) and 60% fine aggregate (ranging from 0 to 4.75 mm), based on the total weight of aggregates, was utilized, and assessed against the guidelines outlined in ACI 211.3R [7]. The specific gravities of fine and coarse aggregates were determined using ASTM C127 [29] and ASTM C128 [30] standards. The specific gravity for fine aggregates was found to be 2.53, while for coarse aggregates it was 2.60. Additionally, the absorption percentages for fine and coarse aggregates were calculated to be 2.35% and 1.34%, respectively.

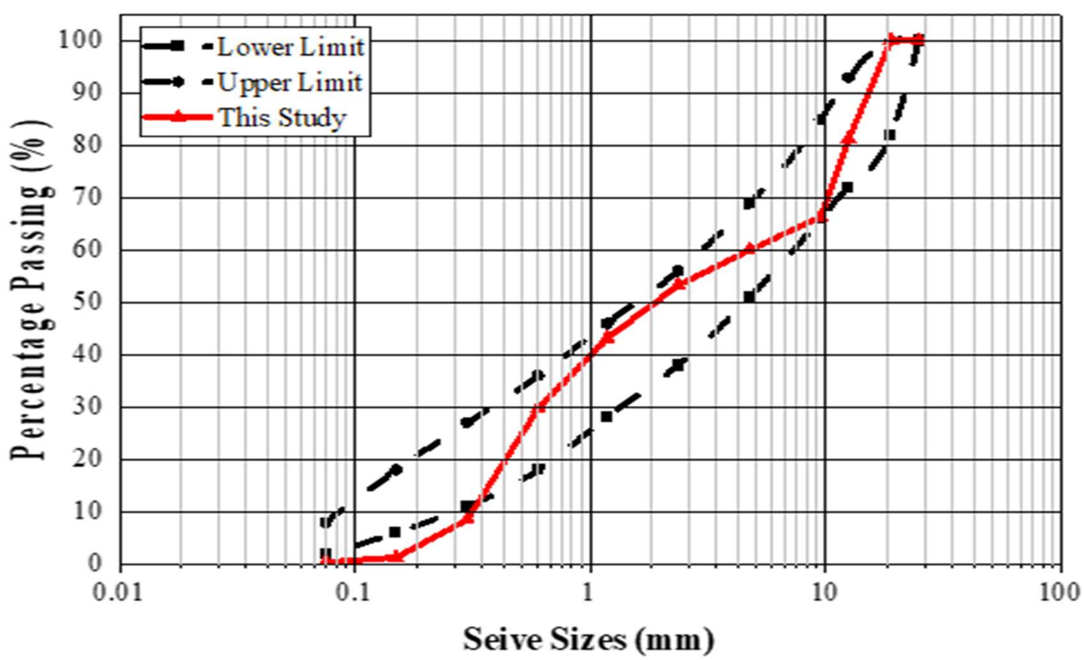


Figure 3.2.3 Combined aggregate gradation of coarse and fine aggregates.

3.3 Experimental mix design

Recent research on alkali-activated concrete [9, 19-22] led to the selection of a mixture of NaOH and Na_2SiO_3 for the activation of GGBFS and FA. To investigate the effect of molarity on AA-RCCP, five distinct molarities of NaOH (4M, 6M, 8M, 10M, and 12M) were chosen. To examine the effect of Na_2SiO_3, different NaOH to Na_2SiO_3 ratios of 3, 2, and 1 were employed for each molarity. As a result, 15 combinations of alkali activators were chosen to evaluate the potential of AA-RCCP. According to ACI 327R-14, cementitious material and moisture content must be specified as a percentage of total dry material in mix design, where dry material consists of cementitious material, coarse aggregates, and fine aggregates [1, 2]. According to the ACI 325.10R-95 guidelines [2], the optimal quantity of cementitious ranges from 10 to 17% by weight of the dry materials. For the calculation of mixed designs, ACI 211.3R instructions were employed [7]. For this research, 17% by weight of dry materials was chosen as a dosage of GGBFS and FA. RCCP is extremely sensitive to moisture, as the optimal amount of moisture is required for maximal compaction. Moisture content below OMC facilitates entrapped air, which causes strength loss, whereas moisture content above OMC increases the water-to-cementitious ratio, which also causes strength loss [2]. In this study, moisture is provided to the AA-RCCP mix through the combination of NaOH and Na_2SiO_3. The viscosity of NaOH increases with the increase of molarity as more flakes are dissolved for increasing concentration. This investigation is complicated by the fact that the viscosity of the mixture of NaOH and Na_2SiO_3 changes as the amount of Na_2SiO_3 varies. OMC varies for each activator combination; therefore, moisture-density relationships for each activator combination were determined by compacting AA-RCCP mixtures in accordance with ASTM D1557 [31] while varying alkali activator dosages. The impact of alkali dosages on compressive strength was also investigated for selective mix designs by testing 100 mm x 200 mm cylinders. For each alkali activator combination, samples were prepared at OMC, and their hardened properties were evaluated. The effect of age of curing and delay in compaction on compressive strength was also investigated. Table 3.3.2 displays the experimental mix formulations containing all AA-RCCP ingredients. 17% of the weight of the dry constituents was chosen as the OPC dosage for the RCCP containing OPC. The OPC-based RCCP is referred to as the control mix, and each property of the AA-RCCP is compared to it. Table 3.3.1 shows the mix proportion for the control mix.

Table 3.1.1 Mix proportion for OPC-RCCP.

Components	**Proportions**
OPC (kg/m^3)	364.80
Water (kg/m^3)	168.17
Fine Aggregates (kg/m^3)	1068.66
Coarse Aggregate (kg/m^3)	712.44
OMC (%)	5.9
Water to Cement ratio (w/c)	0.46

Table 3.3.2 AA-RCCP mix composition at OMC.

Mix	M[i]	R[ii]	OMC (%)	Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m3)	GGBFS (kg/m^3)	FA (kg/m^3)	Na_2SiO_3 Solution (kg/m^3)	NaOH Solution (kg/m^3)	Alkali Activator Composition		
										Water (kg/m^3)	NaOH Solids (kg/m^3)	Na_2SiO_3 Solids (kg/m^3)
4M-3R-5.05w	4	3	5.05	1098.87	732.58	300.09	75.02	37.98	113.95	118.33	16.14	17.47
4M-2R-5.20w	4	2	5.20	1098.83	732.55	300.08	75.02	51.87	103.74	117.06	14.69	23.86
4M-1R-5.4w	4	1	5.4	1101.31	734.21	300.76	75.19	80.44	80.44	112.49	11.39	37.00
6M-3R-5.25w	6	3	5.25	1102.95	735.30	301.21	75.30	39.36	118.07	116.09	23.22	18.10
6M-2R-5.35w	6	2	5.35	1103.28	735.52	301.30	75.32	53.31	106.63	114.44	20.97	24.52
6M-1R-5.65w	6	1	5.65	1102.09	734.73	300.97	75.24	83.60	83.60	112.30	16.44	38.46
8M-3R-5.4w	8	3	5.4	1101.50	734.33	300.81	75.20	40.23	120.69	111.26	31.15	18.51
8M-2R-5.5w	8	2	5.5	1101.71	734.47	300.87	75.22	54.47	108.95	110.24	28.12	25.06
8M-1R-5.85w	8	1	5.85	1099.25	732.83	300.20	75.05	85.87	85.87	110.08	22.16	39.50
10M-3R-5.7w	10	3	5.7	1100.36	733.58	300.50	75.13	42.05	126.14	110.03	38.81	19.34
10M-2R-5.75w	10	2	5.75	1101.16	734.11	300.72	75.18	56.52	113.03	108.77	34.78	26.00
10M-1R-6.25w	10	1	6.25	1094.87	729.91	299.00	74.75	90.51	90.51	111.53	27.85	41.63
12M-3R-6.2w	12	3	6.2	1095.17	730.11	299.08	74.77	44.95	134.86	111.55	47.59	20.68
12M-2R-6.6w	12	2	6.6	1088.63	725.75	297.30	74.32	62.91	125.82	115.39	44.40	28.94
12M-1R-6.8w	12	1	6.8	1087.61	725.08	297.02	74.25	96.78	96.78	114.89	34.15	44.52

[i] Molarity of NaOH = M
[ii] $NaOH/Na_2SiO_3$ = R

3.4 Sample preparation and testing methods

3.4.1 Mixing of RCCP

AA-RCCP mixing procedure differs from that of OPC-RCCP because an alkali activator is added in place of water. The preparation of the RCCP mixture is of paramount importance, as fresh and hardened properties depend significantly on it. The desired molarity of NaOH solution is prepared and mixed in a specific ratio with Na_2SiO_3 solution 24 hours prior to mixing concrete [32-36]. After appropriate dry mixing of fine and coarse aggregate, FA and GGBFS were added to the mixer, and all dry constituents were thoroughly mixed. A solution of NaOH and Na_2SiO_3 was then introduced very slowly while the concrete was being mixed. After the addition of the alkali activator blend, the concrete was mixed for 4-5 minutes.

3.4.2 MDD and OMC specimens

For moisture-density relationships, all RCCP mixtures followed the ASTM D1557 [31] guidelines. A fresh mixture of Roller-Compacted Concrete Pavement (RCCP) was compacted in a mold having a diameter of 152.4 mm and a height of 116.4 mm. The process of compacting fresh concrete involves the sequential compaction of five layers. Each layer is subjected to 56 compactions using a rammer weighing 4.5364 kg and dropped from a height of 457.3 mm. The compaction technique is iterated for every RCCP mixture, employing varying moisture percentages of 4%, 5%, 6%, and 7%. A moisture-density relationship was established by plotting the measured moisture content and dry density values. From this relationship, the optimum moisture content (OMC) and maximum dry density (MDD) were determined. The average value of three specimens was utilized in order to establish the moisture density relationship.

3.4.3 The Casting of RCCP specimens

To conduct RCCP testing, cylindrical specimens measuring 100 mm x 200 mm were manufactured. The process of molding specimens involved the utilization of a vibrating hammer that operated at a frequency of 3800 impacts per minute and required an input voltage of 1300 watts [37]. The vibratory hammer is equipped with a chuck that securely holds a tamping plate. The tamping plate has a mass of 3kg and a diameter of 96 mm. This setup enables accurate and controlled compaction of concrete. The compaction process involved the layering of each cylinder in three successive levels, with each layer being compressed for a period of 20 seconds. When a mortar ring was formed before the 20-second compaction time [37], compaction was stopped. Figure 3.4.3(a) illustrates the process of preparing the RCCP cylindrical specimen, in conjunction with the utilization of a vibratory hammer and tamping plate. The specimens were removed from the molds 24 hours after compaction and thereafter coated in cling wrap to avoid moisture loss. Specimens in the form of beams, with dimensions measuring 100 mm x 100 mm x 400 mm, were fabricated in order to conduct flexural strength tests. The beam specimens were prepared through the process of compacting the fresh mix into two layers. In order to compact the beam specimens, the bottom plate of another beam mold was positioned on top of the fresh mixture, and compaction was performed by means of a tamping plate. The beam specimens were also enveloped in cling wrap in order to facilitate the curing process. Figure 3.4.3(b) displays RCCP beam specimens that have been appropriately prepared and securely covered in cling wrap.

Figure 3.4.3 (a) Casting of RCCP cylinders. (b) Beam specimens wrapped in cling wrap.

3.4.4 Mechanical Properties

In accordance with ASTM C39 [38], RCCP cylindrical specimens with a 100 mm diameter and 200 mm height were tested in a compression testing machine with a continuous loading rate of 0.250 MPa/s. The average value of three samples was considered for the purpose of comparing different RCCP mixes. The failure of the RCCP cylinder under compression is depicted in Figure 3.4.4(a). The split tensile strength testing was conducted on RCCP specimens, according to the guidelines outlined in ASTM C496 [39]. The specimen had a diameter of 100 mm and a height of 200 mm. The configuration of the split tensile test is depicted in Figure 3.4.4(b). The flexural strength of a prism specimen of 100 mm x 100 mm x 200 mm was evaluated using the testing protocol outlined in ASTM C78 [40].

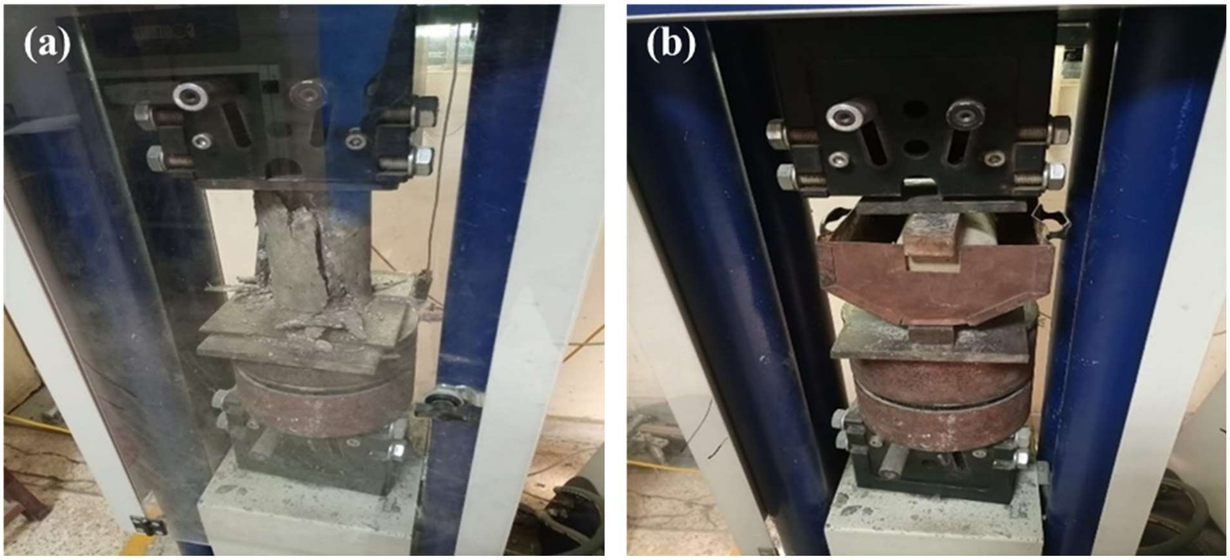


Figure 3.4.4 (a) RCCP compression test. (b) Split tensile strength test of RCCP.

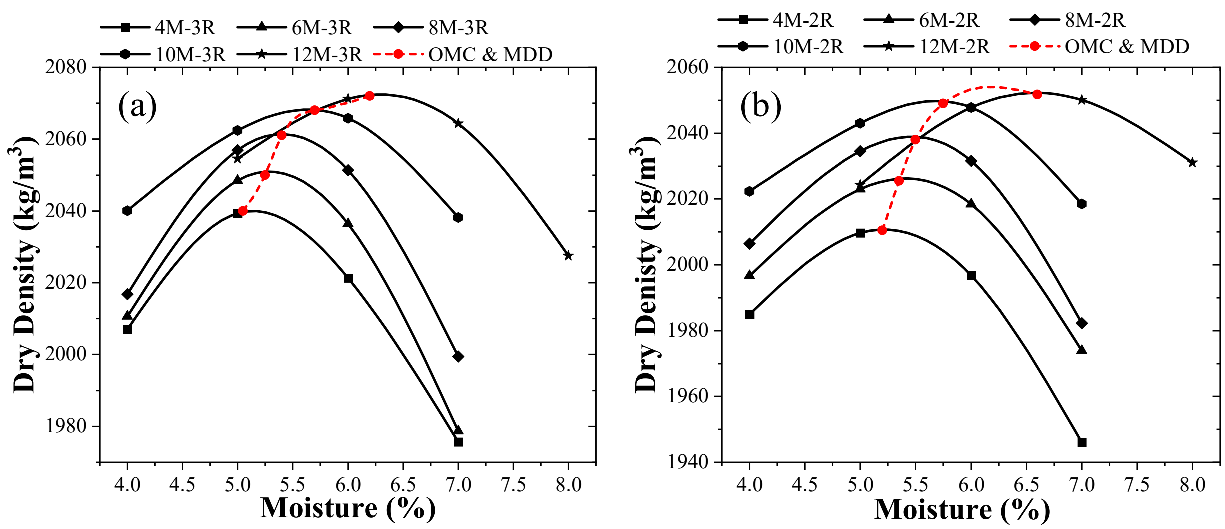
Chapter 4

4 Results and Discussions

4.1 OMC & MDD

4.1.1 Effect of NaOH Molarity on OMC and MDD

The dry density of roller-compacted concrete (RCC) exhibits an initial increase with increasing moisture content. However, below a specific threshold, the dry density experiences a decline during compaction. This decline results in the optimum moisture content (OMC), which is associated with the maximum dry density (MDD) [41, 42]. The specimens of Roller-Compacted Concrete Pavement (RCCP) must undergo molding at the Optimum Moisture Content (OMC) [1], since any deviation from this moisture content value leads to a degradation in strength [2]. A series of five molarities, ranging from 4M to 12M with an increment of two, were varied. For each molarity, the NaOH/Na_2SiO_3 ratios of 3, 2, and 1 were also varied. The ratio between NaOH and Na_2SiO_3 is shown as R in Table 3.3.2, which provides a comprehensive list of the ingredients present in the AA-RCCP mixture. Figure 4.1.1 (a), (b), and (c) depict the impact of varying NaOH molarity on the moisture-density relationship while maintaining a constant NaOH-to-Na_2SiO_3 ratio of 3, 2, and 1, respectively. The moisture-density relationships obtained for all AA-RCCP mixes exhibit similarities to the moisture-density relationships previously discovered by researchers studying RCC [43-45]. Figure 4.1.1 (a), (b), and (c) show that with an increase in the molarity of NaOH, OMC and MDD increase. According to Bastani and Behfarina [9], the presence of NaOH in alkali activator solution causes the hydrogen bonding of water to dissipate, reducing the packing of GGBFS particles and facilitating compaction. This hypothesis supports the increasing density of AA-RCCP due to the increase in the molarity of NaOH, as the AA-RCCP mixture will accomplish greater compaction utilizing the same compaction effort. A similar effect of an increase in density due to an increase in compaction was also observed [46], which provides additional evidence that more compaction is attained as molarity increases. High-density alkali activators are incorporated into the AA-RCCP as the molarity of NaOH increases, providing a second explanation for the system's increasing density behavior. The density of the alkali activator is increased by dissolving more NaOH particles in water, leading to greater molarity. More alkali activator is required to lubricate all the dry ingredients as molarity, density, and viscosity increase. The utilization of a higher density alkali activator and the increased use of a higher-density alkali activator align with the tendency to increase dry density as the molarity of NaOH increases. Researchers also observed a similar trend of increase in dry density when relatively lower-density recycled asphalt aggregates were replaced with relatively higher-density natural aggregates [47, 48]. Figure 4.1.1 (a), (b), and (c) also demonstrate that OMC increases as NaOH molarity increases. The primary factor contributing to the rise in OMC can be primarily attributed to the increase in viscosity of the alkali activator, which is caused by a higher concentration of dissolved particles. In Figure 4.1.1 (a), the OMC rises from 5.05% to 6.2% as the molarity of NaOH increases from 4M to 12M in the 4M-3R and 12M-3R mixtures, respectively. For a fixed quantity of Na_2SiO_3, the alkali activator in mixtures 4M-3R and 12M-3R consisted of 22.12% and 37.97% solids, thus having 77.88% and 62.03% water, respectively. As the quantity of solids in the alkali activator rises, there is a decrease in the amount of water accessible to facilitate lubrication of all the dry ingredients in AA-RCCP mixes. Consequently, a higher amount of alkali activator is required to achieve the optimum moisture content (OMC) as the molarity of NaOH increases.



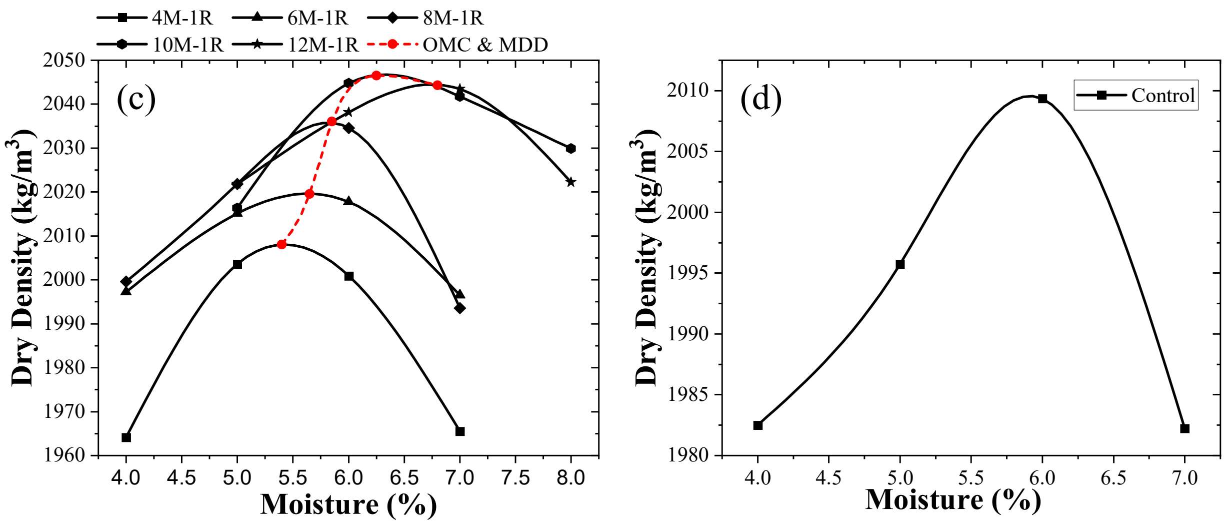
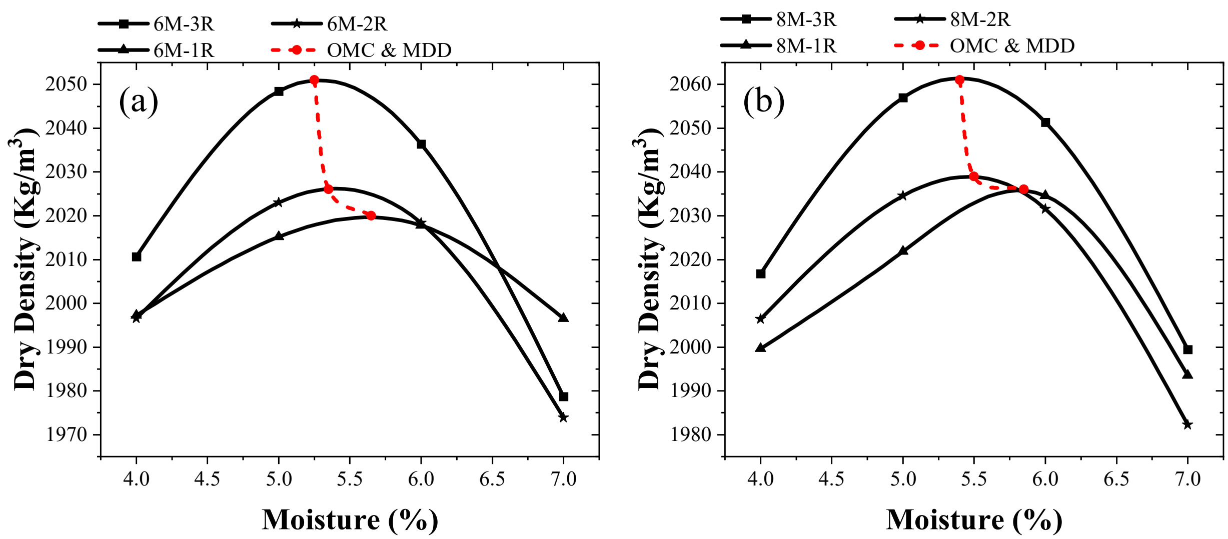


Figure 4.1.1 Effect of NaOH molarity on OMC and MDD for (a) $NaOH/Na_2SiO_3$ = 3 (b) NaOH/Na2SiO3 = 2 (c) NaOH/Na2SiO3 = 1 (d) Control mix.

Figure 4.1.1 (d) illustrates the moisture-density relationship for OPC-RCCP, where the proportion of OPC by weight of the total dry ingredients was 17%. The OPC-RCCP used in this investigation had a water-to-cement ratio of 0.46 and an OMC of 5.9%. According to ACI 327R-14 [1], maintaining a water-to-cement ratio of 0.40 is advantageous for enhanced strength and reduction of permeable pores, which can be attained by using water-reducing admixtures. The AA-RCCP mixes 4M-3R, 4M-2R, and 4M-1R exhibited lower OMC values compared to OPC-RCC, however an increase in NaOH molarity resulted in greater OMC values. The role of fly ash in providing desired workability at lower water demands and the slipperiness offered by the alkali activator can explain the relatively lower OMC of AA-RCCP at lower alkali activator concentrations [9, 49].

4.1.2 Effect of Na_2SiO_3 content on OMC and MDD

In order to demonstrate the impact of Na_2SiO_3 on the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD), the moisture-density graphs corresponding to fixed NaOH molarities of 6, 8, 10, and 12 are reorganized as depicted in Figure 4.1.2 (a), (b), (c), and (d), respectively. Sodium silicate increases in the AA-RCCP as the $NaOH/Na_2SiO_3$ ratio decreases. The increase of Na_2SiO_3 quantities resulted in a reduction in dry density for all constant molarities of NaOH. The stickiness of the freshly prepared AA-RCCP was enhanced due to an increased quantity of sodium silicate. Due to the stickiness of fresh mix, flowability decreases substantially, resulting in resistance to compaction and a reduction in dry density. In a study conducted by Yang and Song [50], it was observed that the inclusion of Na_2SiO_3 resulted in a reduction in the initial workability of alkali-activated mortar. Additionally, it was discovered that sodium hydroxide exhibited a lesser effect on the reduction of workability compared to sodium silicate. The stickiness of AA-RCCP is further supported by the findings of Das and Shrivastava [51], who concluded that the addition of Na_2SiO_3 decreases the workability of a fresh mix while increasing its cohesiveness. The workability of alkali-activated concrete is reduced by the reaction between sodium silicate and extremely concentrated sodium hydroxide, as stated by Bastani and Behfarnia [9]. The availability of highly concentrated NaOH and an abundance of Na_2SiO_3 may provide an explanation for the observed reduction in density of the 12M-1R mixture as the molarity of NaOH increases, as depicted in Figure 4.1.1 (c).



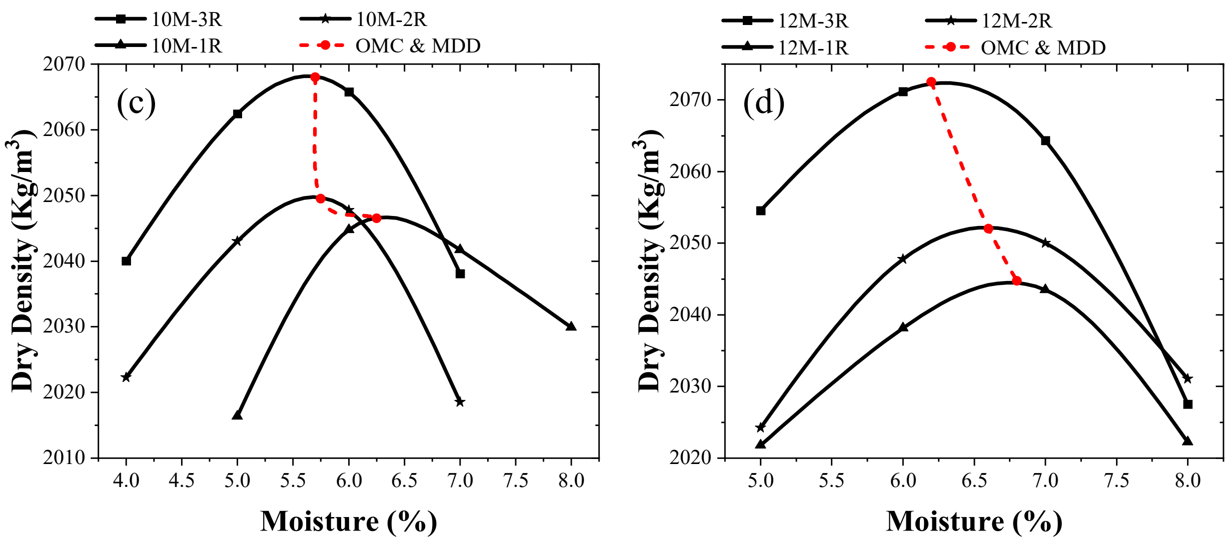
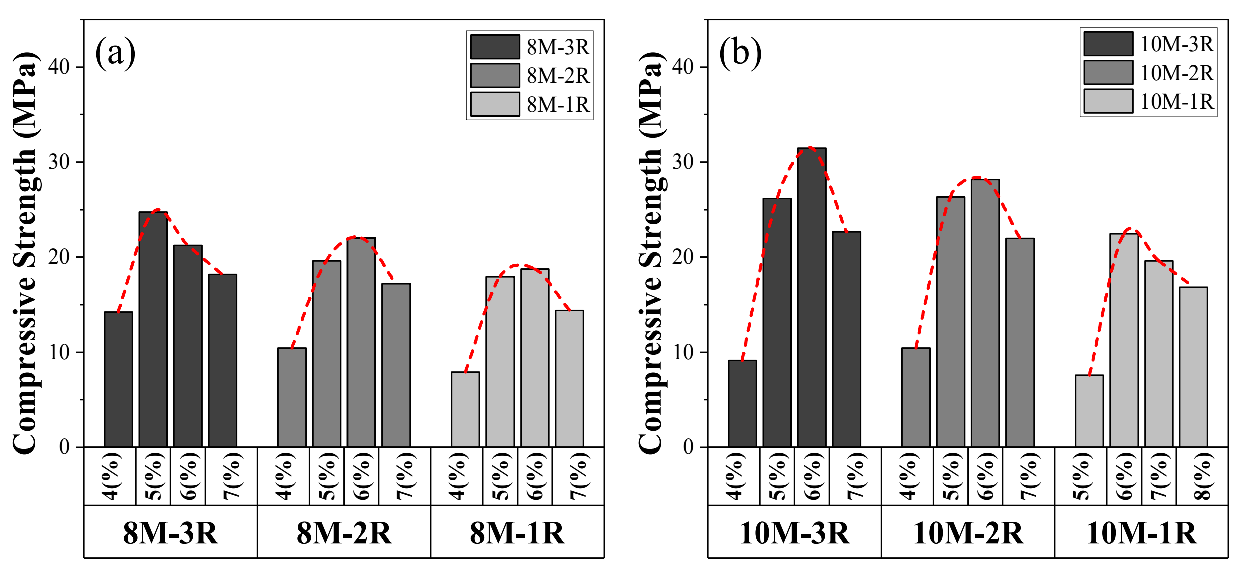


Figure 4.1.2 Effect of $NaOH/Na_2SiO_3$ (R) on OMD and MDD for fixed molarity of (a) 6M, (b) 8M, (c) 10M, and (d) 12M.

The viscosity of alkali activators in AA-RCCP increases with the introduction of greater amounts of sodium silicate, thus leading to an increase in the optimum moisture content (OMC). Mix designs 6M-3R and 6M-1R had respective solid contents of 26.25% and 32.84%, which resulted in residual water content of 73.75% and 67.16%, respectively, for the purpose of lubricating the dry constituents of AA-RCCP. The increase in Na_2SiO_3 content results in the incorporation of a greater number of particles into the alkali activator, leading to a decrease in the available water for lubrication of all the dry ingredients. Consequently, a larger amount of alkali activator is required to facilitate the lubrication of all the dry components, resulting in an increase of the optimum moisture content (OMC). The capacity of Na_2SiO_3 to undergo a reaction with NaOH [9], the reduction in workability [50], and the increase of cohesiveness [51] all together contributed to the overall rise in optimum moisture content (OMC).

4.2 Moisture Content and Compressive Strength

To determine the effect of alkali activator dosage on the compressive strength of AA-RCCP, the 28-day compressive strength of nine AA-RCCP mixes containing four distinct alkali activator dosages was evaluated. Compressive strength in RCCP technology exhibits a high sensitivity to moisture content, similar to dry density. Deviation from the optimum moisture content (OMC) can lead to substantial reductions in strength [2]. In addition to the role of alkali activator content, Figures 4.2 (a), (b), and (c), respectively, illustrate the effect of $NaOH/Na_2SiO_3$ on compressive strength for fixed molarities of 8M, 10M, and 12M; however, the effect of change in molarity on compressive strength can be observed by comparing them. For OPC-RCCP, a variation of water in place of an alkali activator was done, and the effect on compressive strength is shown in Figure 4.2 (d). In the case of all Roller-Compacted Concrete Pavement (RCCP) mixtures, it was noticed that the compressive strength increased as the moisture content approached the optimum moisture content (OMC) value. However, further increasing the moisture content beyond the OMC resulted in a diminishing influence on the compressive strength. The 8M-3R mixture, with an optimum moisture content (OMC) of 5.4%, exhibited a significant 73.85% gain in compressive strength after 28 days when the moisture level was raised from 4% to 5%, as depicted in Figure 4.2 (a). Conversely, a fall of 14.25% in compressive strength was recorded when the moisture content was further increased from 5% to 6%. According to Figure 4.2, it can be observed that both AA-RCCP and OPC-RCC exhibit a significant dependence on the optimum moisture content (OMC). Any deviation from the OMC can result in a reduction in compressive strength. In a study conducted by AliAhmed et al. [52], the researchers examined the impact of moisture content on compressive strength. They found that when the moisture content was below the optimum moisture content (OMC), it was insufficient for achieving maximum compaction, leading to a reduction in strength. Strength loss from increasing moisture content compared to OMC is often less than strength loss from decreased moisture content compared to OMC in the majority of AA-RCCP design mixes, which is consistent with the findings of other studies [46, 52].



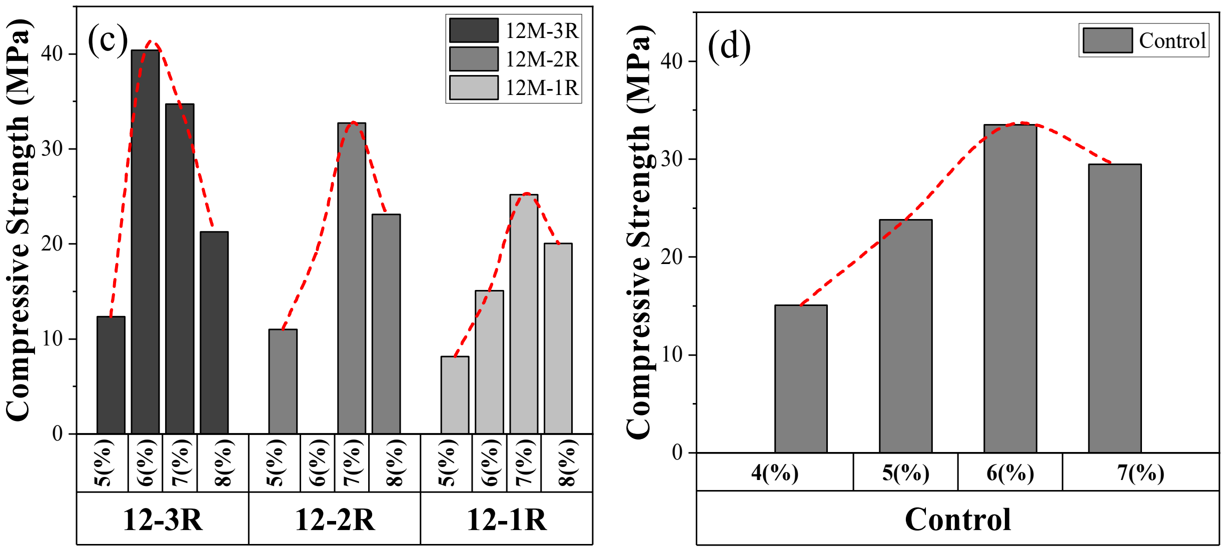


Figure 4.2 The effect of moisture content on compressive strength.

Due to insufficient lubrication of all dry constituents of RCCP, maximum compaction cannot be accomplished when the moisture content is below OMC, resulting in decreased density and compressive strength. When moisture content exceeds OMC, the ratio of water to binder increases for both AA-RCCP and OPC-RCCP, resulting in a decrease in compressive strength [53]. Increased moisture content also increases workability, and during the first few seconds of compaction of RCCP in accordance with ASTM C1435 [37], a mortar ring appears. Compaction of RCCP fresh mix after the formation of a mortar ring squeezes out the mortar during the molding of a cylindrical specimen [37], resulting in segregation and a decrease in compressive strength. As shown in Figure 4.2 (a), (b), and (c), the compressive strength decreases with the increase in Na_2SiO_3 content. As shown in Figure 4.1.2, this diminishing effect is due to a decrease in dry density with increasing Na_2SiO_3 content. When comparing Figure 4.2 (a), (b), and (c), it is clear that an increase in compressive strength occurs when NaOH molarity rises. Hadi et al. [19] investigated the impact of NaOH molarity on the combination of GGBFS and FA in geopolymer concrete and found that an increase in concentration has a very strong impact on compressive strength. This is because an increase in NaOH concentration dissolves more solids, which increases the potential for geopolymer reaction and, consequently, increases the compressive strength. Increasing the concentration of NaOH decreases the water-to-binder ratio for constant alkali activator dosages, thereby enhancing the compressive strength of concrete [53]. Similar to this study, Yomthong et al. [8] examined the effect of molarity on fly ash-based geopolymer concrete by varying the concentration of NaOH from 4M to 12M and discovered that an increase in NaOH concentration results in increased strength.

4.3 Mechanical Properties of RCCP concrete mixtures

4.3.1 Compressive Strength

The compressive strength results of all the RCCP mixtures having optimum dosages of alkali activator are shown in Figure 4.3.1. For each design mix, the effect of 7 days and 28 days of curing on compressive strength is examined, while curing of the AA-RCCP specimen was accomplished by wrapping specimens in cling wrap to prevent moisture loss. This method is frequently replicated on-site by covering the RCCP surface with a white cement layer or an asphalt overlay [1]. For each molarity of NaOH, an increase in Na_2SiO_3 causes a decrease in compressive strength, and this loss of strength increases as the NaOH concentration increases. For the 4M molarity of NaOH in the design mixes 4M-3R and 4M-1R, the compressive strength at 28 days decreases from 19.35 MPa to 15.68 MPa, representing a strength loss of 18.97% due to an increase in Na_2SiO_3 content. In mix designs 12M-3R and 12M-1R, the compressive strength decreases by 35.51 %, from 44.41 MPa to 28.64 MPa, as a result of the increase in Na_2SiO_3 content. An increase in Na_2SiO_3 content decreases compressive strength for all AA-RCCP mixtures, whereas strength loss increases for AA-RCCP mixtures with a high NaOH concentration. As the concentration of NaOH increased from 4M to 12M in the design mixes 4M-3R and 12M-3R, 28-day compressive strengths of 19.34 MPa and 44.41 MPa were observed, representing an increase of 129.63% in compressive strength. By reacting with alkali activators, the aluminium-silicate-rich raw ingredients in alkali-activated concrete form chemical compounds that reinforce the concrete. This reaction is highly dependent on the hydroxide ion (OH), which increases with increasing NaOH concentration, resulting in a greater quantity of calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) gels, which boost compressive strength. [8, 23]. Approximately 14 MPa to 63 MPa of compressive strength was also observed when the molarity of NaOH was increased from 4M to 12M in self-compacting alkaline-activated concrete. [54].

7-day and 28-day compressive strengths for mix design 4M-3R were 13.74 MPa and 19.35 MPa, respectively, resulting in an increase of 40.83 percent in strength. For mix design 4M-1R, the compressive strength at 7 days and 28 days with a 58.70% increase were 9.88 MPa and 15.68 MPa, respectively. With an increase in Na_2SiO_3, the early strength of AA-RCCP decreases, and the strength gain between 7 and 28 days increases, resulting in an increase in ultimate strength. Only a 12.36% strength gain was observed for 12M-3R between 7 and 28 days. The results of compressive strength indicate that the early strength of AA-RCCP increases with increasing NaOH concentration; however, increasing Na_2SiO_3 content enhances the gain in strength at later ages. OPC-RCCP specimens were cured in a curing tank containing tap water. Similar to conventional concrete, compressive strengths of 24.28 MPa and 37.50 MPa were measured after 7 and 28 days of curing, indicating a 54.45% increase in strength. ACI 327R-14 states that the compressive strength of RCC typically falls between 28 MPa and 40 MPa. In this investigation, seven mix designs met the minimum compressive strength threshold in 28 days: 8M-3R, 10M-3R, 10M-2R, 12M-3R, 12M-2R, 12M-1R, and OPC-RCCP.

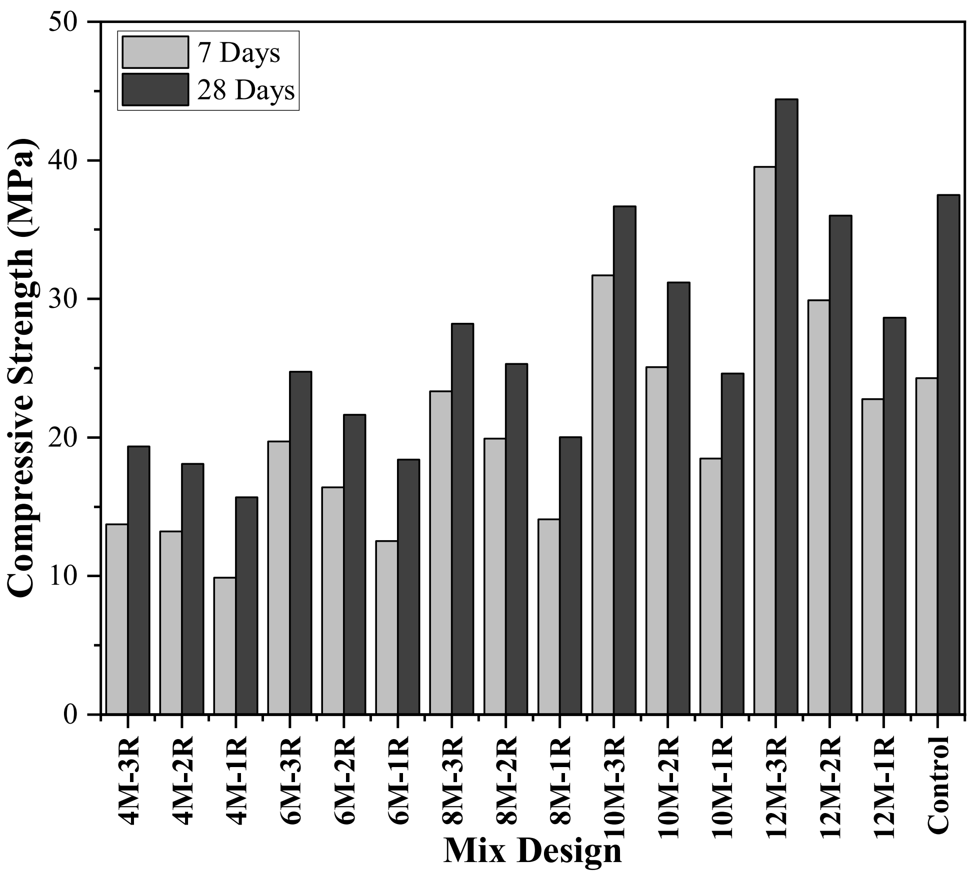


Figure 4.3.1 Compressive strength of RCCP at OMC.

4.3.2 Flexural Strength

Mix designs with a fixed NaOH-to-Na_2SiO_3 ratio of 3 and an incremental increase in molarity were tested to capture the flexural response of AA-RCCP due to an increase in the molarity of NaOH. For investigating the effect of Na_2SiO_3, the NaOH-to-Na_2SiO_3 ratio was varied between 3, 2, and 1 for a fixed 10M NaOH concentration. Figure 4.3.2 depicts the results for the 28-day flexural strength of RCCP beams. AA-RCCP, with a molarity of less than 8 M, has a reduced flexural strength compared to OPC-RCCP. ACI 327R-14 [1] specifies that the flexural strength of RCCP should range between 3.5 and 7 MPa. The flexural strength of mix designs 4M-3R, 6M-3R, and 10M-1R was lower than both the ACI 327R-14 [1] lower limit and the OPC-RCCP. Similar to compressive strength, flexural strength increases as NaOH molarity increases and decreases as Na_2SiO_3 content increases.

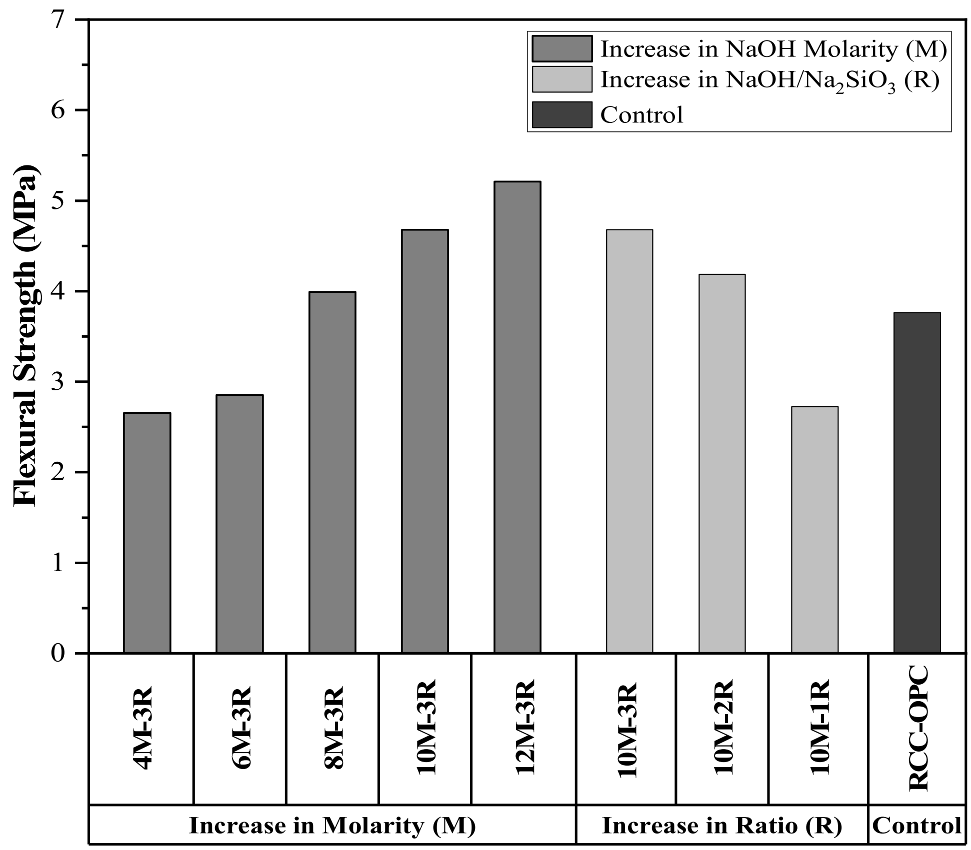


Figure 4.3.2 Flexural Strength results for RCCP mixtures.

4.3.3 Split tensile strength

The split tensile strength of all the RCCP mixtures was also tested and compared with OPC-RCCP. Typically, for design purposes, the tensile response of concrete is ignored to the extent of zero. However, in exceptional circumstances, such as the design of highways, airfield slabs, and fracture resistance, the tensile response of concrete can be of paramount importance [55]. Figure 4.3.3 displays test results for 28-day split tensile strength. Except for mix design 12M-3R, all AA-RCCP mixtures demonstrated lower split tensile strength than OPC-RCCP mixtures. The higher split tensile strength of OPC-RCCP specimens may also be the result of better curing compared to AA-RCCP specimens. No upper or lower limit for tensile strength has been specified by any standard for RCCP technology; however, based on the literature on RCCP technology, split tensile strength for RCCP under typical conditions ranges between 2 MPa and 4 MPa [56, 57]. In the current study, mix designs 4M-1R and 12M-2R exhibited a minimum tensile strength of 1.40 MPa and a maximum compressive strength of 3.74 MPa, respectively. The split tensile strength improved by 58.05% from 2.36 MPa to 3.74 MPa when the NaOH concentration was raised from 4M to 12M in the 4M-3R and 12M-3R mix designs. Split tensile strengths of 3.30 MPa and 2.34 MPa, respectively, were observed, representing a decrease of 29.09% due to an increase in Na_2SiO_3 content in both the 10M-3R and 10M-1R mix designs.

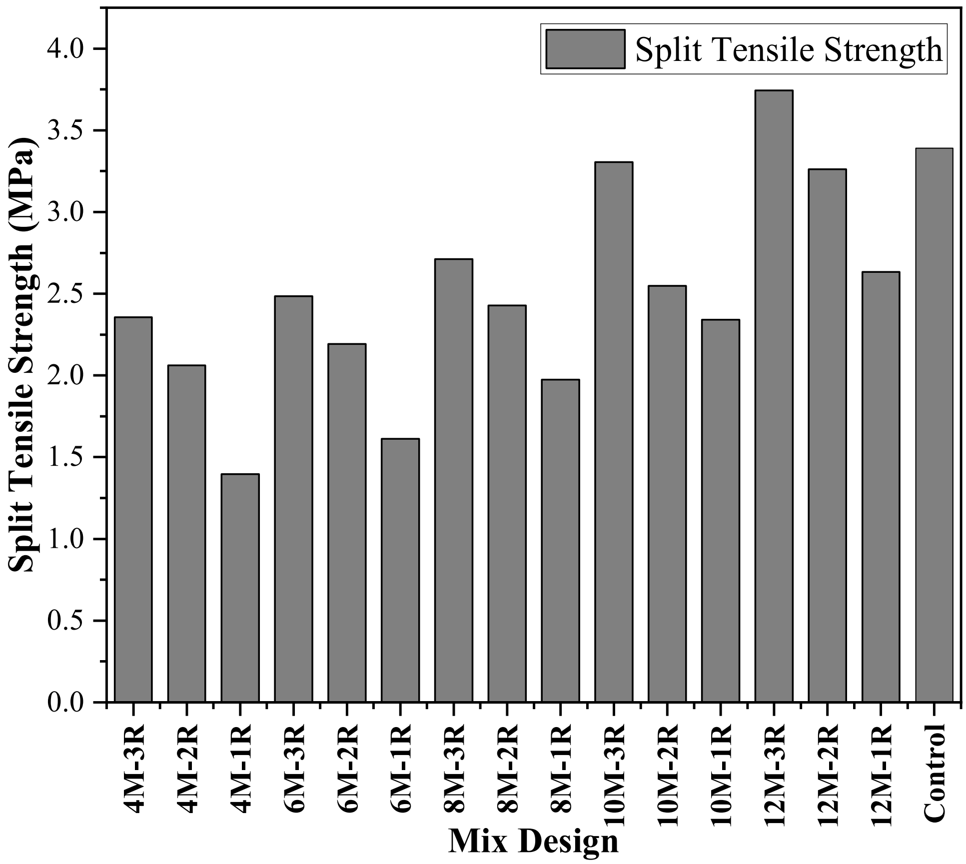
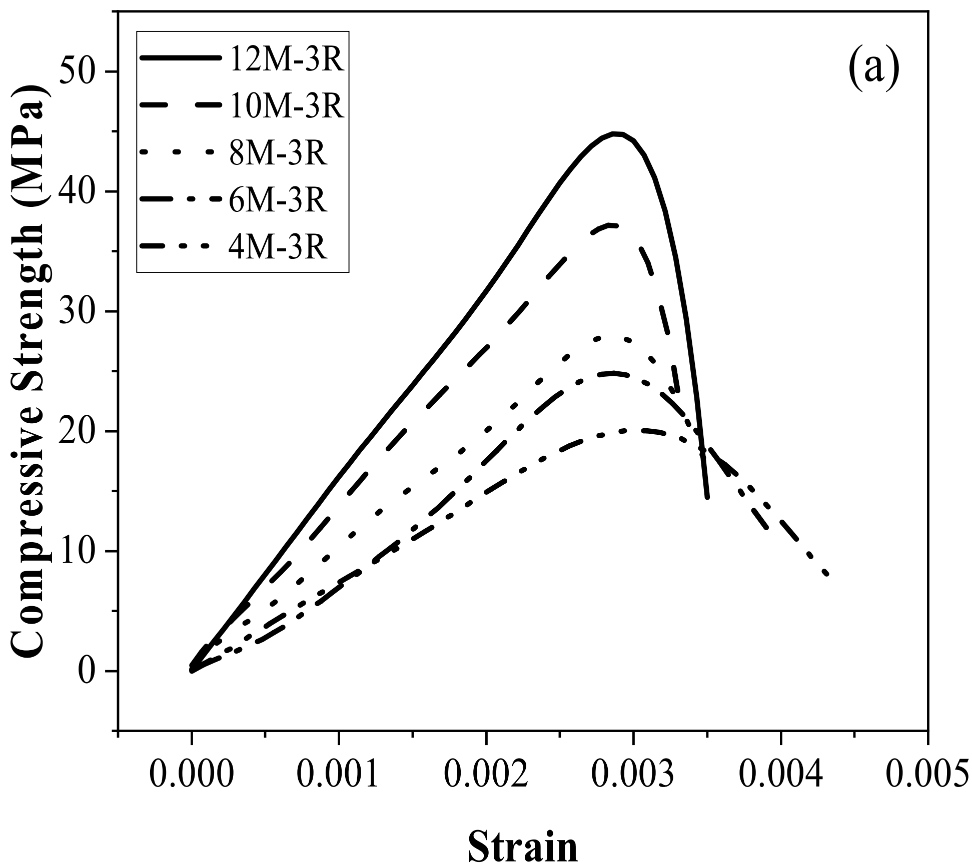


Figure 4.3.3 Split tensile strength results for all RCCP mix designs.

4.3.4 Stress-Strain curves

Stress-strain curves of AA-RCCP mix compositions for a fixed NaOH-to-Na_2SiO_3 ratio of 3 and increasing molarity from 4M to 12M were also developed and is displayed in Figure 4.3.4 (a). Maximum peak stress of 19.962 MPa and 45.110 MPa was observed in 4M-3R and 12M-3R, respectively, which shows a 125.98% increase. The slope of stress strain curves increases with the increase in peak stress. The peak stress of all tested specimens was observed approximately at a strain of 0.003. Specimens with higher peak stress showed less post-peak response than specimens with lower peak stress. The modulus of elasticity (E) calculated according to ASTM C469 [58] increased as the molarity of NaOH increased. The modulus of elasticity increased by 91% as the molarity of NaOH increased from 4M to 12M having a constant NaOH/Na_2SiO_3 ratio of 3. In order to observe the effect of Na_2SiO_3 on the modulus of elasticity, stress-strain curves for a fixed molarity of 10M with NaOH-to-Na_2SiO_3 ratios of 3, 2, and 1 are depicted in Figure 4.3.4 (b). The modulus of elasticity decreased by 64.28% as the proportion of Na_2SiO_3 increased in mix designs 10M-3R and 10M-1R. This indicates that stiffness and load-carrying capacity reduce significantly as the content of Na_2SiO_3 increases in the alkali activator solution.



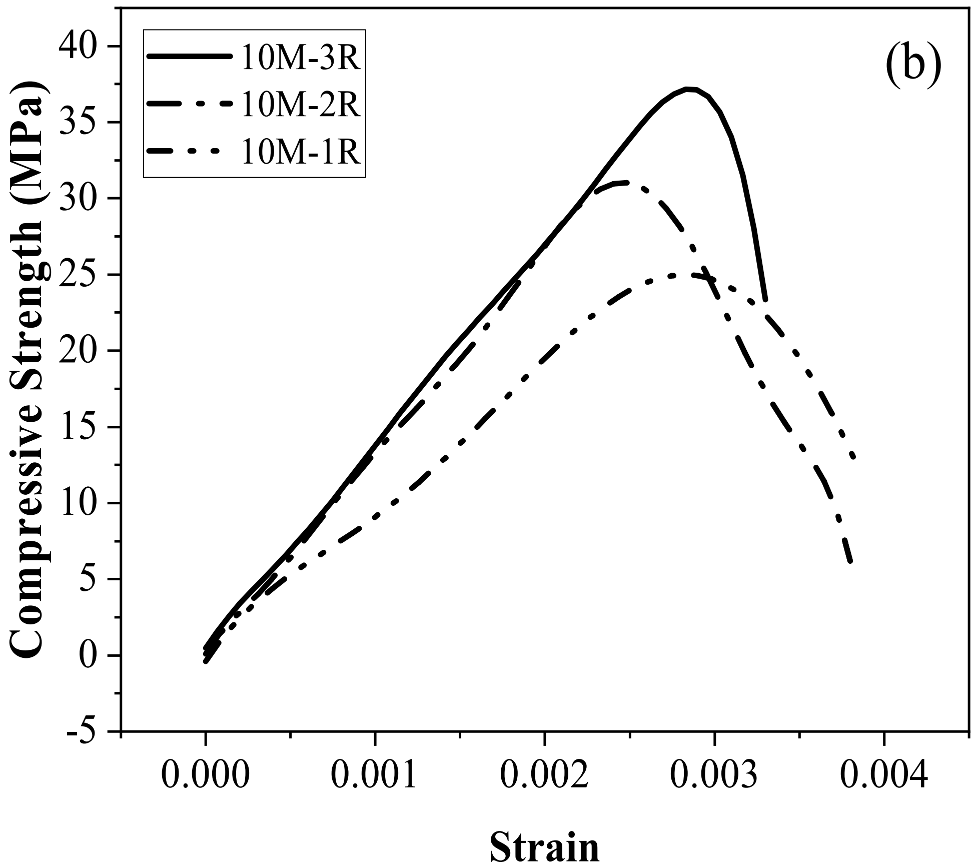


Figure 4.3.4 Stress-strain curves for AA-RCCP.

4.4 Effect of Dry Density and Void Ratio on compressive strength

Based on the moisture-density relationships depicted in Figures 4.1.2 and 4.2, it was determined that compressive strength is highly dependent on the OMC, which aids in attaining maximum density. The maximum density obtained for all AA-RCCP design mixtures is compared to compressive strength in order to examine the effect of dry density on compressive strength, as depicted in Figure 4.4.1. With a constant Na_2SiO_3 quantity, increasing the molarity of NaOH increased the dry density of all AA-RCCP mixtures. The compressive strength of all AA-RCCP specimens increases with an increase in dry density. The strong correlation between dry density and compressive strength in Figure 4.4.1 indicates that dry density has a substantial effect on RCCP strength. Meddah et al. [14] also observed a strong influence of dry density on compressive strength when natural aggregates were substituted for shredded rubber tire aggregates.

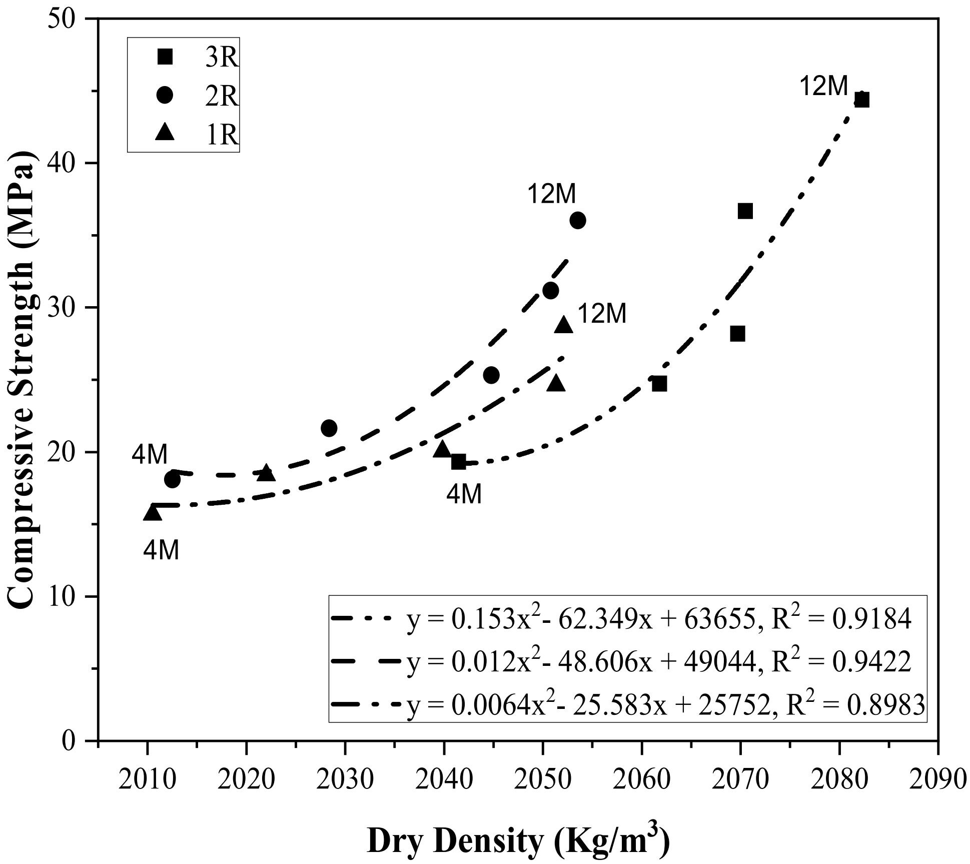


Figure 4.4.1 Effect of dry density on compressive strength of AA-RCCP.

In this study, the soil compaction method is used for proportioning and testing RCCP, which requires maximal concrete compaction similar to that of soil, using ASTM D1557 guidelines [31]. Using the test results such as dry density, wet density, and moisture content from ASTM D1557 [31], as well as the known mix proportion for RCCP, void ratio, porosity, and air content can be calculated for RCCP employing geotechnical weight-volume relationships [59]. Figure 4.4.2 provides a visual representation of how the void ratio influences compressive strength. For a fixed Na_2SiO_3 content, the void ratio decreases as the molarity of NaOH increases, resulting in an increase in compressive strength. Rehman and Khattak [23] also established a relationship between void ratio and compressive strength and concluded that with the increase in the molarity of NaOH in fly ash roller compacted concrete, the void ratio decreases. By comparing Figure 4.4.1 and Figure 4.4.2, it can be noticed that as the dry density of AA-RCCP increases, the void ratio decreases. A strong correlation between compressive strength and void ratio suggests that void ratio has a significant impact on compressive strength. By comparison of Figures 4.4.1 and 4.4.2 it can be noticed that as the amount of Na_2SiO_3 in AA-RCCP increased, the dry density decreased, and the void ratio increased, respectively. Both a decrease in dry density and an increase in the void ratio are responsible for the weakening of AA-RCCP, which supports the diminishing effect of Na_2SiO_3 on the mechanical properties of AA-RCCP.

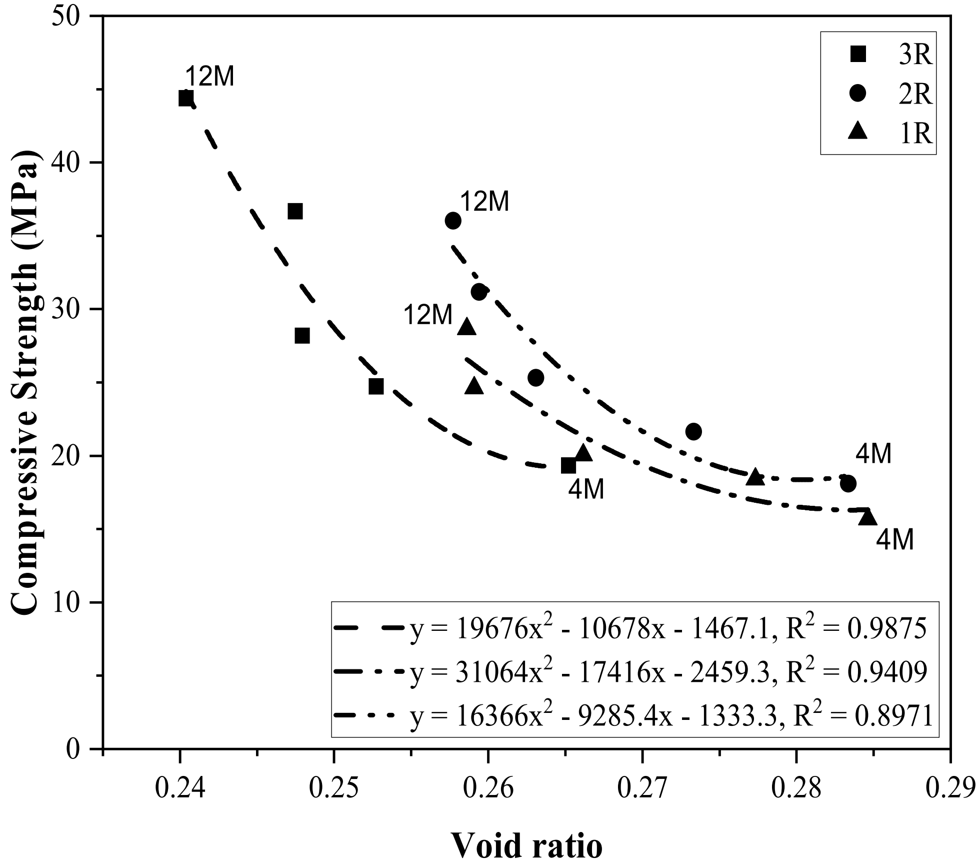


Figure 4.4.2 Effect of void ratio on compressive strength.

4.5 Effect of delay in compaction on compressive strength

Fresh RCCP mixture is mixed at the mixing plant and transported to the paver hopper using dump trucks during site implementation. A delay in the compaction of fresh mix reduces the workability of RCCP, which affects its strength. To prevent a significant loss of strength, ACI 327R-14 [1] limits the transportation time to 45 minutes. A fresh AA-RCCP mixture was prepared and compacted at several intervals of time to observe the response of AA-RCCP due to delayed compaction. Mix designs 12M-3R, 12M-1R, 10M-3R, and 10M-1R were chosen to examine the effect of delay in compaction on 28-day compressive strength and were compared to OPC-RCCP.

For each design mix, a fresh mix of RCCP was prepared and compacted after 5, 10, 30, 45, and 60 minutes of addition of the alkali activator. As the time between mixing and compaction increased, strength loss was observed in all the RCCP formulations, as shown in Figure 4.5. For OPC-RCCP, the compressive strength at 28 days was 37.50 MPa, 36.65 MPa, 31.19 MPa, 28.46 MPa, and 24.07 MPa after delays of 5, 10, 30, 45, and 60 minutes, respectively, indicating a strength loss of 0%, 2.24%, 16.83%, 24.11%, and 35.81%. Due to the reduced setting time associated with the use of an alkali activator, AA-RCCP mixtures exhibited a greater loss of strength than the OPC-RCCP mixture. When the delay in compaction was increased from 5 minutes to 30 minutes, the strength loss with increasing Na_2SiO_3 content in 12M-3R and 12M-1R mixes also increased from 22.56% to 52.89%, respectively. When the time between mixing and compaction was increased from 5 minutes to 30 minutes, the strength loss with increasing NaOH molarity, in mix designs 10M-3R and 12M-3R, was 19.96% and 22.56%, respectively. The strength loss increases with the increase in the molarity of NaOH, which confirms that setting time reduces with the increase in the concentration of NaOH. However, the strength loss due to an increase in Na_2SiO_3 content is significantly greater than the strength loss due to an increase in NaOH concentration, indicating that with an increase in Na_2SiO_3 content, setting time reduces significantly more than due to an increase in NaOH concentration. Similar observations were also reported by Laskar and Talukdar [60], who found that Na_2SiO_3 had a greater impact on setting time than NaOH.

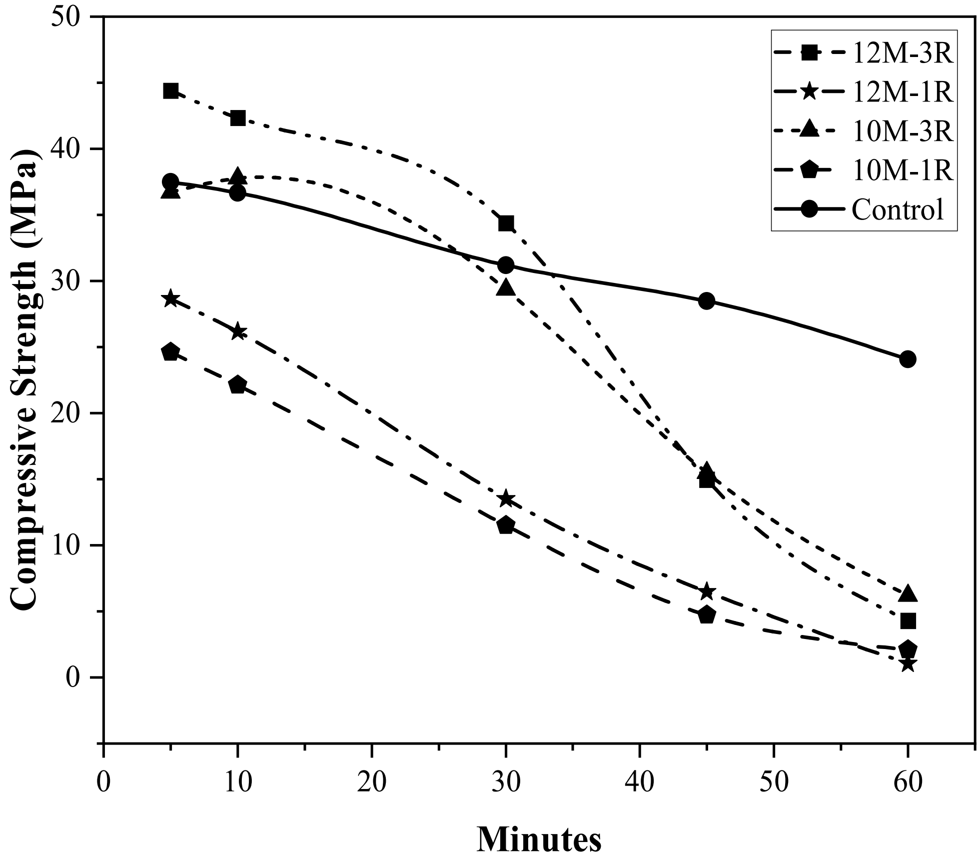


Figure 4.5 Effect of delay in compaction on compressive strength.

Based on the test results shown in Figure 4.5, the optimal range of transportation time for mix designs 12M-3R and 10M-3R is between 20 and 30 minutes. With increased Na_2SiO_3 content in mix designs 12M-1R and 10M-1R, the optimal range of transport time decreased to 5 to 10 minutes. In addition, it should be noted that a delay in compaction was observed during the summer season in Islamabad, where, according to the Pakistan Meteorological Department [61], the maximum temperature can easily exceed 40 degrees Celsius. At lower temperatures, the optimal delay time for compaction may be longer. With a 10-minute delay in compaction, the 28-day compressive strength increased in mix design 10M-3R. A. Karimpour [62] conducted extensive research on the effect of the time interval between mixing and compaction and found a similar trend when 25% of the cement was replaced with GGBFS. He concluded that compaction of RCC during the formation of the crystallized net, which is responsible for strength, increases compressive strength, whereas compaction after the formation of the crystallized net decreases compressive strength.

4.6 Effect of curing age on compressive strength of RCCP

Compressive strength was tested on AA-RCCP at 7, 28, 56, and 90 days of curing for the 12M-3R, 12M-1R, 10M-3R, and 10M-1R mix designs and compared to OPC-RCCP at the same ages. Figure 4.6 demonstrates that as the curing age increases, the compressive strength increases in all RCCP specimens; however, the increase in compressive strength in the OPC-RCCP design mix is substantially greater than that of the AA-RCCP design mixes. After 7, 28, 56, and 90 days of curing, the compressive strengths of the OPC-RCCP design mix were 24.28 MPa, 37.50 MPa, 40.31 MPa, and 41.20 MPa, respectively. After 7 and 28 days of curing, OPC-RCCP gained 58.93% and 91.02% of its 90-day compressive strength, respectively. After 28 days of curing, 99% and 98.5% of the 90-day compressive strengths were observed for mix designs 10M-3R and 12M-3R, respectively. This indicates that an increase in NaOH molarity causes an increase in high early strength phenomena, which is in line with findings of Wardhono et al. [63]. High early strength phenomena can be attributed to an increased NaOH concentration, which accelerates the development of strength-developing products. Due to the increase in Na_2SiO_3 content in 12M-3R and 12M-1R, 98.47% and 84.92% of the 90-day strength were achieved at 28 days of curing. This discovery suggests that an increased amount of Na_2SiO_3 leads to a decrease in strength gain at early age. This observation aligns with the results reported by Gebregziabiher et al. [64]. According to ACI 327R-14 [1], a minimum compressive strength of 14 to 17 MPa is required for light vehicles to pass, which can be readily obtained after 7 days of curing for selected AA-RCCP mix designs.

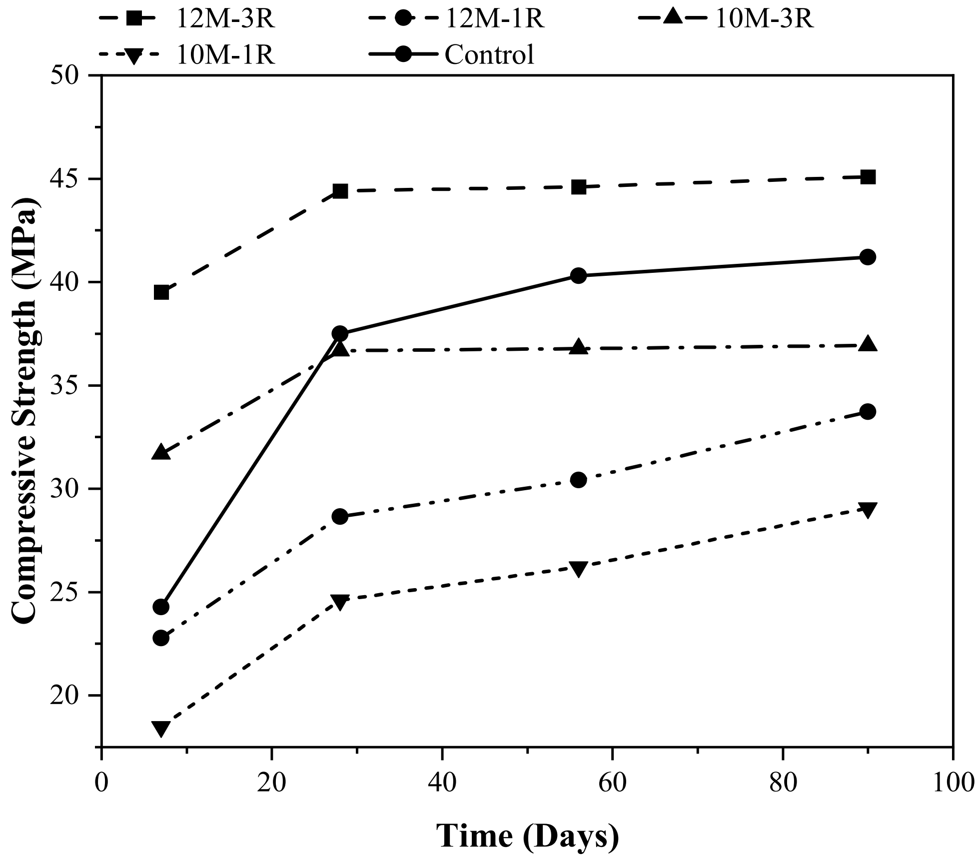


Figure 4.6 Effect of curing age on compressive strength.

Chapter 5

5 Conclusions and Recommendations

5.1 Conclusions

In this study, AA-RCCP concrete was produced via the integration of RCCP technology, and Alkali activated concrete (AAC) technology. In order to optimize the performance of AA-RCCP, the fresh and hardened properties of 15 optimal mix designs were evaluated by varying the proportions and concentrations of Na_2SiO_3 and NaOH. Investigations into the fresh and cured properties of AA-RCCP led to the following conclusions:

- OMC and MDD increase as the concentration of NaOH in the alkali activator solution increases. The percentage of solids increases as the molarity of NaOH increases, leaving behind less water to lubricate all the dry constituents of AA-RCCP and necessitating a greater amount of alkali activator. With an increase in the molarity of NaOH, the MDD rises due to the inclusion of a higher-density NaOH solution and the ability of the fresh AA-RCCP mix to facilitate compaction as a result of the presence of NaOH, which decreases the packing density of fly ash and slag particles.
- OMC increases while MDD decreases as the Na_2SiO_3 proportion increases in the alkali activator solution. As the proportion of Na_2SiO_3 increases in alkali activator solution, the amount of water available for lubrication of dry constituents of AA-RCCP decreases, necessitating a larger quantity of alkali activator solution to achieve OMC. An increase in the Na_2SiO_3 proportion in the alkali activator solution reduces the workability and increases the cohesion (stickiness) of the fresh AA-RCCP mixture, resulting in resistance to compaction and a decrease in MDD.
- For each AA-RCCP mix design, alkali activator dosages that deviate from the corresponding OMC value will result in a decrease in strength. A lesser amount of alkali activator than OMC fails to lubricate all the dry constituents, preventing maximum compaction and thereby reducing the compressive strength. Alkali activator dosage greater than that of OMC increases the water-to-binder ratio and decreases the capacity of fresh AA-RCCP to be compacted, thereby lowering its compressive strength.

- Mechanical parameters such as compressive strength, flexural strength, split tensile strength, and modulus of elasticity improve with increasing NaOH molarity for all AA-RCCP mix designs. The improvement in mechanical properties is due to the increased production of strength-developing gels. As the amount of Na_2SiO_3 in the alkali activator increased, the mechanical properties of AA-RCCP diminished due to a decrease in density.
- Compressive strength is highly correlated with dry density and void ratio. The compressive strength increases as the dry density increases and decreases as the void ratio increases. Other mechanical properties of AA-RCCP are likewise expected to have a substantial association with dry density and void ratio.
- All RCCP specimens lose strength as the time between mixing and compaction increases; however, this loss is greater in AA-RCCP specimens compared to OPC-RCCP specimens due to their shorter setting time.
- When compared to OPC-RCC, AA-RCCP shows a more rapid increase in strength over time. In AA-RCCP mix formulations, an increase in NaOH concentration accelerates the production of strength-developing products, resulting in high early strength.

5.2 Recommendations

- Rate of reaction of alkali activated concrete can be controlled using set retarders which can increase the time interval of mixing and compaction without significant reduction in mechanical properties.
- Durability studies related to this relatively new technology is a research gap and is highly recommended to study.

References

1. Committee, A.C.I., *327R-14: Guide to Roller-Compacted Concrete Pavements.* Technical Documents.
2. Committee, A.C.I., *Abstract of: State-of-the-Art Report on Roller Compacted Concrete Pavements.* ACI Materials Journal, 1994. **91**(5).
3. Lisbona, P., et al., *Techno-economic assessment of an industrial carbon capture hub sharing a cement rotary kiln as sorbent regenerator.* International Journal of Greenhouse Gas Control, 2021. **112**: p. 103524.
4. Malhotra, V., *Global warming, and role of supplementary cementing materials and superplasticisers in reducing greenhouse gas emissions from the manufacturing of portland cement.* International Journal of Structural Engineering, 2010. **1**.
5. Naik, T.R., *SUSTAINABILITY OF CEMENT AND CONCRETE INDUSTRIES*, in *Achieving Sustainability in Construction*. p. 141-150.
6. Davidovits, J., *Geopolymer Chemistry and Applications*. Vol. 171. 2008.
7. *211.3R-97: Standard Practice for Selecting Proportions for No-Slump Concrete.* Technical Documents.
8. Yomthong, K., et al., *Effect of NaOH Concentration and Curing Regimes on Compressive Strength of Fly Ash-Based Geopolymer.* Materials Today: Proceedings, 2021. **43**: p. 2647-2654.
9. Bastani, M. and K. Behfarnia, *Application of alkali-activated slag in roller compacted concrete.* International Journal of Pavement Research and Technology, 2020. **13**(3): p. 324-333.
10. Hazaree, C., H. Ceylan, and K. Wang, *Influences of mixture composition on properties and freeze–thaw resistance of RCC.* Construction and Building Materials, 2011. **25**(1): p. 313-319.
11. Nili, M. and M. Zaheri, *Deicer salt-scaling resistance of non-air-entrained roller-compacted concrete pavements.* Construction and Building Materials, 2011. **25**(4): p. 1671-1676.
12. Courard, L., F. Michel, and P. Delhez, *Use of concrete road recycled aggregates for Roller Compacted Concrete.* Construction and Building Materials, 2010. **24**(3): p. 390-395.
13. Madhkhan, M., R. Azizkhani, and M.E. Torki Harchegani, *Effects of pozzolans together with steel and polypropylene fibers on mechanical properties of RCC pavements.* Construction and Building Materials, 2012. **26**(1): p. 102-112.
14. Meddah, A., M. Beddar, and A. Bali, *Use of shredded rubber tire aggregates for roller compacted concrete pavement.* Journal of Cleaner Production, 2014. **72**: p. 187-192.
15. Rao, S.K., P. Sravana, and T.C. Rao, *Abrasion resistance and mechanical properties of Roller Compacted Concrete with GGBS.* Construction and Building Materials, 2016. **114**: p. 925-933.
16. Rao, S.K., P. Sravana, and T.C. Rao, *Investigating the effect of M-sand on abrasion resistance of Fly Ash Roller Compacted Concrete (FRCC).* Construction and Building Materials, 2016. **118**: p. 352-363.
17. Hesami, S., et al., *Mechanical properties of roller compacted concrete pavement containing coal waste and limestone powder as partial replacements of cement.* Construction and Building Materials, 2016. **111**: p. 625-636.

18. Fakhri, M. and F. Saberi. K, *The effect of waste rubber particles and silica fume on the mechanical properties of Roller Compacted Concrete Pavement.* Journal of Cleaner Production, 2016. **129**: p. 521-530.
19. Hadi, M.N.S., N.A. Farhan, and M.N. Sheikh, *Design of geopolymer concrete with GGBFS at ambient curing condition using Taguchi method.* Construction and Building Materials, 2017. **140**: p. 424-431.
20. Nath, P. and P.K. Sarker, *Effect of GGBFS on setting, workability and early strength properties of fly ash geopolymer concrete cured in ambient condition.* Construction and Building Materials, 2014. **66**: p. 163-171.
21. Nuaklong, P., V. Sata, and P. Chindaprasirt, *Influence of recycled aggregate on fly ash geopolymer concrete properties.* Journal of Cleaner Production, 2016. **112**: p. 2300-2307.
22. Bernal, S.A., et al., *Effect of binder content on the performance of alkali-activated slag concretes.* Cement and Concrete Research, 2011. **41**(1): p. 1-8.
23. Rahman, S.S. and M.J. Khattak, *Roller compacted geopolymer concrete using recycled concrete aggregate.* Construction and Building Materials, 2021. **283**.
24. *ASTM C618-23, Standard Specification for Coal Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*. 2023, ASTM International: West Conshohocken, PA.
25. *ASTM C430-17, Standard Test Method for Fineness of Hydraulic Cement by the 45 μm (No. 325) Sieve*. 2017, ASTM International: West Conshohocken, PA.
26. *ASTM C188 − 17 (Reapproved 2023), Standard Test Method for Density of Hydraulic Cement*. 2017, ASTM International: West Conshohocken, PA.
27. *ASTM C150/C150M-22, Standard Specification for Portland Cement*. 2022, ASTM International: West Conshohocken, PA.
28. *ASTM C136/C136M-19, Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates*. 2019, ASTM International: West Conshohocken, PA.
29. *ASTM C127-15, Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate*. 2015, ASTM International: West Conshohocken, PA.
30. *ASTM C128-22, Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate*. 2022, ASTM International: West Conshohocken, PA.
31. *ASTM D1557 − 12 (Reapproved 2021), Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft3 (2,700 kN m/m3))*. 2012, ASTM International: West Conshohocken, PA.
32. Davidovits, J., *Geopolymer.* Chemistry and Applications. Institute Geopolymere, Saint-Quentin, France, 2008.
33. Khan, I., et al., *Risk of early age cracking in geopolymer concrete due to restrained shrinkage.* Construction and Building Materials, 2019. **229**: p. 116840.
34. Nguyen, K.T., T.A. Le, and K. Lee, *Evaluation of the mechanical properties of sea sand-based geopolymer concrete and the corrosion of embedded steel bar.* Construction and Building Materials, 2018. **169**: p. 462-472.
35. Ruengsillapanun, K., et al., *Mechanical properties, shrinkage, and heat evolution of alkali activated fly ash concrete.* Construction and Building Materials, 2021. **299**: p. 123954.
36. Saloni, et al., *Performance enhancement of rubberised-alkali-activated-concrete utilising ultra-fine slag and fly ash.* Cleaner Materials, 2022. **4**: p. 100080.
37. *ASTM C1435/C1435M − 20, Standard Practice for Molding Roller Compacted Concrete in Cylinder Molds Using a Vibrating Hammer*. 2020, ASTM International: West Conshohocken, PA.

38. *ASTM C39/C39M-21, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*. 2021, ASTM International: West Conshohocken, PA.
39. *ASTM C496/C496M − 17, Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens*. 2017, ASTM International: West Conshohocken, PA.
40. *ASTM C78/C78M-22, Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)*. 2022, ASTM International: West Conshohocken, PA.
41. Aghaeipour, A. and M. Madhkhan, *Effect of ground granulated blast furnace slag (GGBFS) on RCCP durability.* Construction and Building Materials, 2017. **141**: p. 533-541.
42. Modarres, A. and Z. Hosseini, *Mechanical properties of roller compacted concrete containing rice husk ash with original and recycled asphalt pavement material.* Materials & Design, 2014. **64**: p. 227-236.
43. Saluja, S., et al., *Assessing the effect of GGBS content and aggregate characteristics on drying shrinkage of roller compacted concrete.* Construction and Building Materials, 2019. **201**: p. 72-80.
44. Lam, M.N.-T., S. Jaritngam, and D.-H. Le, *Roller-compacted concrete pavement made of Electric Arc Furnace slag aggregate: Mix design and mechanical properties.* Construction and Building Materials, 2017. **154**: p. 482-495.
45. Rad, S.A.M. and A. Modarres, *Durability properties of non-air entrained roller compacted concrete pavement containing coal waste ash in presence of de-icing salts.* Cold Regions Science and Technology, 2017. **137**: p. 48-59.
46. Qasrawi, H.Y., I.M. Asi, and H.I.A.-A. Wahhab, *Proportioning RCCP mixes under hot weather conditions for a specified tensile strength.* Cement and Concrete Research, 2005. **35**(2): p. 267-276.
47. Debbarma, S., G.D. Ransinchung R.N, and S. Singh, *Feasibility of roller compacted concrete pavement containing different fractions of reclaimed asphalt pavement.* Construction and Building Materials, 2019. **199**: p. 508-525.
48. Settari, C., et al., *Assessing the effects of recycled asphalt pavement materials on the performance of roller compacted concrete.* Construction and Building Materials, 2015. **101**: p. 617-621.
49. Khatib, J.M., *Performance of self-compacting concrete containing fly ash.* Construction and Building Materials, 2008. **22**(9): p. 1963-1971.
50. Yang, K.-H. and J.-K. Song, *Workability Loss and Compressive Strength Development of Cementless Mortars Activated by Combination of Sodium Silicate and Sodium Hydroxide.* Journal of Materials in Civil Engineering, 2009. **21**(3): p. 119-127.
51. Das, S.K. and S. Shrivastava, *Influence of molarity and alkali mixture ratio on ambient temperature cured waste cement concrete based geopolymer mortar.* Construction and Building Materials, 2021. **301**: p. 124380.
52. AliAhmad, M., M. Miri, and M. Rashki, *Probabilistic and experimental investigating the effect of pozzolan and Lumachelle fine aggregates on roller compacted concrete properties.* Construction and Building Materials, 2017. **151**: p. 755-766.
53. Yang, K.-H., A.-R. Cho, and J.-K. Song, *Effect of water–binder ratio on the mechanical properties of calcium hydroxide-based alkali-activated slag concrete.* Construction and Building Materials, 2012. **29**: p. 504-511.

54. K, N.V. and D.L.V. Babu, *Assessing the performance of molarity and alkaline activator ratio on engineering properties of self-compacting alkaline activated concrete at ambient temperature.* Journal of Building Engineering, 2018. **20**: p. 137-155.
55. Neville, A.M. and J.J. Brooks, *Concrete technology*. Vol. 438. 1987: Longman Scientific & Technical England.
56. Atiş, C.D., et al., *Strength properties of roller compacted concrete containing a non-standard high calcium fly ash.* Materials Letters, 2004. **58**(9): p. 1446-1450.
57. Chi, M. and R. Huang, *Effect of circulating fluidized bed combustion ash on the properties of roller compacted concrete.* Cement and Concrete Composites, 2014. **45**: p. 148-156.
58. *C469/C469M − 14,Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression*. 2014, ASTM International: West Conshohocken, PA.
59. Das, B.M., *Fundamentals of Geotechnical Engineering*. 2012: Cengage Learning.
60. Musaddiq Laskar, S. and S. Talukdar, *Development of Ultrafine Slag-Based Geopolymer Mortar for Use as Repairing Mortar.* Journal of Materials in Civil Engineering, 2017. **29**(5): p. 04016292.
61. *Pakistan Meteorological Department*. 2023; Available from: https://nwfc.pmd.gov.pk/new/monthly-reports.php.
62. Karimpour, A., *Effect of time span between mixing and compacting on roller compacted concrete (RCC) containing ground granulated blast furnace slag (GGBFS).* Construction and Building Materials, 2010. **24**(11): p. 2079-2083.
63. Wardhono, A., et al., *Comparison of long term performance between alkali activated slag and fly ash geopolymer concretes.* Construction and Building Materials, 2017. **143**: p. 272-279.
64. Gebregziabiher, B.S., R. Thomas, and S. Peethamparan, *Very early-age reaction kinetics and microstructural development in alkali-activated slag.* Cement and Concrete Composites, 2015. **55**: p. 91-102.