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Sustainable Concrete with Beneficial
Byproducts

SP-334

Editor:
Moncef L. Nehdi



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Sustainable Concrete with Beneficial Byproducts

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PREFACE

Sustainable Concrete with Beneficial Byproducts

To improve the eco-efficiency and sustainability of concrete, the cement and concrete industry can exploit many byproducts in applications that could, in some cases, outperform conventional materials made with traditional ingredients. This Special Publication of the American Concrete Institute Committee 555 (Concrete with Recycled Materials) is a contribution towards improving the sustainability of concrete via using recycled materials, such as scrap tire rubber and tire steel wire fiber, GFRP waste, fluff, reclaimed asphalt pavements, recycled latex paint, and recycled concrete aggregate. Advancing knowledge in this area should introduce the use of recycled materials in concrete for applications never considered before, while achieving desirable performance criteria economically, without compromising the quality and long-term performance of the concrete civil infrastructure.

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Mechanical Performance of Concrete Incorporating Slender Elements from Recycling GFRP Waste

Yuan Tian and Ardavan Yazdanbakhsh

Synopsis: Due to their unique mechanical characteristics, glass fiber reinforced polymer (GFRP) composite materials are difficult to recycle at the end of their service lives. In the present work, a specific approach of recycling GFRP waste for use in concrete is investigated. Scrap from GFRP rebar and waste from a GFRP wind turbine blade shell were processed into slender elements, referred to as “needles,” with a length of 100 mm and used in concrete to replace 5% and 10% of natural coarse aggregate. The results of testing various concrete specimens revealed that the incorporation of needles with longitudinally aligned glass fibers increased the splitting tensile strength of concrete significantly. Both types of recycled needles, regardless of the source of waste and orientation of glass fibers, increased the tensile toughness of concrete significantly. In addition, it was observed that incorporating needles did not reduce concrete’s slump, due to the relatively high specific surface area of the needles. The findings suggest that recycling GFRP waste into needles as concrete reinforcement may be a viable GFRP waste management strategy and deserves further research.

Keywords: Concrete, Discrete reinforcement, GFRP waste, Mechanical performance, Recycled composites

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INTRODUCTION

Concrete is one of the most widely used construction materials. However, it has several shortcomings, one of which is the labor-intensive and time-consuming preparation and placement of continuous steel reinforcement. Discrete reinforcing elements, which can be added during mixing concrete, can partially eliminate this shortcoming. Currently, fibers are the only widely researched and commercialized type of discrete reinforcing elements. Fibers increase the post-failure toughness of hardened concrete, but significantly reduce the workability of fresh concrete due to their high specific surface area. Chemical admixtures that cause additional cost and environmental impacts are required to improve the workability of fresh fiber-incorporated concrete. Moreover, when used beyond limited dosages, fibers tend to agglomerate, resulting in poor reinforcement and formation of weak zones in concrete. For this reason, the dosages of fibers used in concrete are typically limited to about 0.5% of concrete volume.

The present work discusses a different type of discrete reinforcing element with low specific surface area. These elements, hereafter referred to as “needles,” are rod-shape, slender and stiff. The needles studied in the present work are produced by cutting the end-of-life waste of glass fiber reinforced polymer (GFRP) composite materials. The mechanism by which needles function in concrete as reinforcement is fundamentally different from that of commercially used fibers [1-2]. Needles have relatively low aspect ratios, large diameters and, as mentioned earlier, low specific surface areas. Therefore, they do not tend to agglomerate or reduce the workability of concrete. In addition, because needles can be produced from GFRP waste, their use can be environmentally beneficial. Despite the rapid growth in the use of GFRP materials, landfilling and incineration are the primary methods for managing GFRP [3]. Processing the GFRP waste into discrete reinforcing elements for use in concrete is a potential approach to mitigate the environmental burdens of managing GFRP waste.

Several studies have been conducted on the use of GFRP waste in concrete, to extend the use phase of GFRP composite materials. The scope of those studies can be divided into two categories; using pulverized or shredded GFRP waste to partially replace fine aggregate, and using the cut pieces of the waste to partially replace coarse aggregate in concrete. Tittarelli and Correia explored the possibility of replacing fine aggregate in mortar and concrete with powdered GFRP [4-5]. The test results revealed that using GFRP powder has negative impacts on the mechanical properties of both concrete and mortar. Shahria Alam reported reduction in compressive strength and flexural strength of concrete when flat square pieces of GFRP scraps from waterslides were used as a partial replacement of coarse aggregate [6]. Yazdanbakhsh et al. found that the full and partial replacement of coarse aggregate with aggregate-shape cut pieces of GFRP rebar scrap has a

negative impact on the compressive strength, and more so, on the splitting tensile strength of concrete [7-9].

The mechanisms by which needles and fibers resist the growth of the cracks in concrete are fundamentally different [2]. When fiber reinforced concrete (FRC) is subjected to increasing external load and a propagating crack intersects a fiber, high tensile strain develops in the fiber in the zone between the crack surfaces, resulting in a high shear stress in the interface between the fiber and cementitious matrix in the zone close to the crack. This shear stress may result in debonding which progresses toward the end of the fiber, after which the fiber will start to move out of its groove at one side of the crack. The fiber may break before or during pullout. Efficient needles have high flexural stiffness values and have high strength in both tension and shear. Therefore, the only way for a concrete crack bridged by an inclined needle to grow in width is that the concrete encasing the needles crumbles and/or spalls in at least one side of the crack. Additionally, because of the larger size and high stiffness of GFRP-needles, they can function as both discrete reinforcement and coarse aggregate in concrete.

This work presents studies on GFRP Needles recycled from two different waste sources, which were used as partial replacement of coarse aggregate in concrete. The studies investigate the effect of the needles on a number of important mechanical properties of concrete. Details on the production of the two types of needles and testing concrete incorporating them are presented separately in two articles by the authors [1-2]. The present work summarizes and compares the results of those studies, and discusses the parameters that affect the effectiveness of recycled GFRP needles as concrete reinforcing elements.

EXPERIMENTAL PROGRAM

Materials

The two types of GFRP waste used in the experiments are (i) scrap from the production of GFRP reinforcing bars (rebars), and (ii) a piece of GFRP shell from a dismantled wind turbine blade. The GFRP scrap constituted high quality but short GFRP rebars which were cut off during production in a pultrusion plant due to occasional production problems. The rebars have a diameter of 6mm and are sand-coated and helically wrapped by an additional strand of fiber to enhance the bond to concrete. The mechanical properties of the GFRP rebar provided by the manufacturer are presented in Table 1. The GFRP rebar needles were produced by cutting the scrap rebars with a diamond saw into small sections with a length of 100 mm (4 in) (Figure 1), resulting in an aspect ratio of 17. The length is the upper limit beyond which even distribution and orientation of needles in the mold used in the present study would be impacted. And the resulting aspect ratio distinct the needles from fibers.

The 25 mm (1 in) thick waste wind blade shell plate used for producing needles was provided by the Wind Technology Testing Center (WTTC) of National Renewable Energy Lab. A table saw was used to cut the shell into 100 mm long elements with a square cross-section and a side length of 6 mm (0.24 in) (aspect ratio of 15). Compared with the sand coated and helically wrapped GFRP rebar needles, the surface of wind blade needles are smoother. To promote the bond between concrete and embedded needles, half of the produced wind blade needles were grooved with shallow notches perpendicular to the long axis of the needles (Figure 1). The effects of the plain and grooved needles on the performance of concrete were investigated separately. The specific gravity of the wind blade needles is 1.95. and their tensile strength was estimated to be within a

wide range from 35 MPa (5000 psi) to 1,150 MPa (167 ksi), depending on the alignment of glass fibers relative to needle axis [2].

Crushed granite with a nominal maximum size of 19 mm (3/4 in) and a specific gravity of 2.7 was used as coarse aggregate. The particle size distribution of the coarse aggregate was graded to comply with the limits specified by ASTM C33 for No.56 aggregate. An ASTM graded manufactured sand with a specific gravity of 2.58 was used. The fineness modulus of the fine aggregate is 3.1. Type I/II Portland cement with specific gravity of 3.15 was used in all concrete mixtures. Tap water was used for both concrete production and curing the concrete specimens in an environmental chamber.

Concrete mixtures

The proportions of constituents of all the concrete mixtures are presented in Table 2. Control concrete mixtures were proportioned to achieve the compressive strength values typically prescribed by the designers of reinforced concrete structures. Needle-incorporated mixture proportions are the same as those of control mixtures with the exception that predetermined portions (5% and 10% by volume) of coarse aggregate were replaced with needles. Since the water absorption capacities of the GFRP needles are very low, the magnitudes of mixing water were not adjusted to account for the negligible amounts of water absorbed by the needles.

Test specimens and procedures

For each of the three batches in the first phase of the study investigating GFRP rebar needles (1st Series) 6 cylinders with a diameter of 150 mm and a height of 300 mm were cast, three of which were tested to measure compressive strength, and the other three were tested to measure splitting tensile strength. Similarly, 8 cylinders of the same size were produced for each of the five batches in the second phase of the study investigating GFRP wind blade needles (2nd Series). Four of the cylinders were used to measure compressive strength and the remaining four were used to measure splitting tensile strength.

Although cylinder molds with the largest commonly used dimensions (150 mm (6 in) in diameter and 300 mm (12 in) in height) were used for compressive and splitting tensile strength tests, the length of the needles was two third of the cylinder diameter. This relatively large length was expected to affect the spatial distribution of the needles in the cylinders. Slump tests were conducted on all batches according to ASTM C143/C143M [10] after concrete was removed from the mixer. Visual examination was conducted to monitor the consistency of fresh concrete mixtures and detect signs of segregation and agglomeration of needles. The specimens were demolded 24 hours after casting and transferred to an environmental chamber with a relative humidity of 98%. All the specimens from the same mixture were tested on the same day, 28 days after casting. A few hours before testing, the specimens were removed from the curing chamber, wiped dry with towels, and placed in the testing laboratory. The specimens designated for measuring compressive strength were first tested to measure static modulus of elasticity according to ASTM Standard C469/C469M [11] and then tested to measure compressive strength [12]. Two strain gages were attached at the mid-point along the length of each specimen, on the diametrically opposite sides. The strain gauges have a strain capacity of 0.05, much higher than the strain of the concrete specimens when subject to a load 40% of their bearing capacity. Neoprene pads were also placed at both ends of cylindrical specimens to uniformly distribute the applied axial pressure. ASTM C469 permits measuring modules of elasticity prior to measuring compressive strength if the strain gauges attached to the specimens are flexible or protected.

RESULTS AND DISCUSSION

Fresh concrete properties

The slump test results from both phases of the experiments are presented in Table 3. The differences between the slumps of GFRP needle incorporated concretes and those of the control groups are insignificant. These results show that superplasticizers are not needed for needle incorporated concrete mixtures to keep the slump similar to that of the corresponding control concrete; an advantage that cannot be achieved when producing fiber reinforced concrete (FRC). The insignificant effect of GFRP needles on workability can be contributed to the similar specific surface areas of the needles and the coarse aggregates that they replace in concrete. The slump of GRV-10 concrete was slightly lower than those of other concrete batches, potentially due to the higher surface area of the grooved needles. Visual observations during mixing and casting concrete revealed that the needles did not agglomerate and had a relatively random distribution in concrete. Neither agglomeration of GFRP needles nor segregation of GFRP needles from the concrete mixtures were observed.

Hardened concrete properties

Performance in compression. The results of the compressive strength and modulus of elasticity tests are presented in Table 4. Compared with the corresponding control groups, the average compressive strengths of the specimens with 5% and 10% rebar needle replacement were 5.5% and 8.7% lower, respectively. This reduction of compressive strength is insignificant and within the margin of error. Similarly, the replacement ratios of 5% and 10% for plain wind blade needles, and 5% and 10% for grooved wind blade needles resulted in -1.4%, 0.3%, 7.2%, and -4.4% change in compressive strength, respectively. All of the above-mentioned changes are similarly of low significance despite the differences between the physical and mechanical characteristics of rebar and wind blade needles. The insignificant impact of the needles on compressive strength can be due to the low dosage of the needles in concrete (3.5% or less, by volume); the concrete matrix surrounding the needles is the primary component contributing to compressive strength. The results also show that incorporating needles did not have a significant impact on the modulus of elasticity of concrete, which can be similarly explained by the low content of the needles in concrete.

Splitting tensile strength. The splitting tensile strengths of the concrete specimens are presented in Table 4. The splitting tensile strength of the specimens in which 5% and 10% of coarse aggregates were replaced with GFRP rebar needles were respectively 22% and 33% higher than that of the corresponding control concrete. However, the average splitting tensile strength of none of the wind blade needle incorporated concretes was significantly higher than that of the corresponding control concrete. The average splitting tensile strengths of the specimens with 5% plain wind blade needle, 10% plain wind blade needle, 5% grooved wind blade needle, and 10% grooved wind blade needle are lower than that of control specimens by 13.7%, 0.0%, 13.1%, and 7.8%, respectively.

Visual observation of the specimens after splitting tests showed that the control specimens broke into two separate pieces immediately after the peak load, while all GFRP incorporated specimens remained one-piece despite the formation of multiple cracks (Figure 2 and Figure 3). Figure 4 shows the load-displacement curves from the splitting tests. All GFRP incorporated concretes have much higher post-failure toughness and post-failure strain compared to the control groups. Among the GFRP incorporated concrete groups, both GFRP rebar incorporated specimen groups have higher toughness than any of the wind blade needle incorporated specimen groups. This finding

suggests that needles, regardless of their performance in tension, can notably increase the energy absorption capacity of concrete. Visual inspection of the fractured surfaces of the specimens after testing revealed that, both GFRP rebar needles and wind blade needles achieved relatively uniform and random distribution in the concrete cylinders (Figure 5). Figure 5a shows that none of the rebar needles were broken. However, in wind blade needle incorporated specimens, broken needles were observed at the crack surfaces (Figure 5b).

It was hypothesized that the relatively inferior tensile performance of the concretes with wind blade needles is caused by the orientation of glass fibers in the needles. ASTM D2584 ignition loss test [13] was conducted on 10 randomly selected wind blade needles to burn off the resin matrix and determine the orientation of glass fibers. Observation of the specimens with burnt-off resin revealed that glass fibers were mostly perpendicular to the axis of the wind blade needles, while the glass fibers in GFRP rebars are all aligned with the needle axis (Figure 6). Therefore, the findings show a strong correlation between the direction of glass fibers in GFRP needles and the mechanical performance of concrete incorporating the needles. It can therefore be concluded that the waste from GFRP products with unidirectional fibers, such as GFRP rebars or other GFRP components produced by pultrusion method, have the potential for being recyclable into elements that effectively enhance the mechanical performance of concrete.

SUMMARY AND CONCLUSIONS

In this study, large slender elements from processing waste GFRP products were used to partially replace the coarse aggregate in concrete in order to study their influence on a number of important mechanical characteristics of concrete. The needles were produced from two different types of GFRP waste; rebars and a wind turbine blade. Compressive strength, modules of elasticity, and splitting tensile strength of concrete specimens with different needle contents were measured. The test results showed that the needles produced from GFRP rebar scrap improved the splitting tensile strength of concrete significantly. However, the needles produced from wind blade waste had no significant positive influence on the tensile strength. Both types of GFRP needle increased the post-peak toughness of concrete significantly.

The results of the studies presented in this work show that when glass fibers are parallel to the axis of GFRP needles, these slender elements can notably enhance the mechanical performance of concrete. GFRP needles with longitudinally aligned glass fibers have high tensile strength and high Young's modulus values. In addition, when the diameter of GFRP needles is sufficiently large the high flexural stiffness of the needles prevents them from bending over the cracks that intersect them, and therefore prevent the needles from pulling out of their groove. Based on the presented findings it is concluded that recycling GFRP waste with unidirectional embedded fibers into needles for use in concrete may be a viable strategy for beneficial use. Experimental and numerical studies need to be conducted to determine the optimum geometry of needles for application in different structural concrete members.

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This study was supported by New York State Energy Research and Development Authority (NYSERDA) under the grant C2CUNY1 by the PowerBridgeNY Program. Many thanks to Mr. Doug Gremel from Owens Corning for providing the GFRP reinforcing bar production waste and technical information. The authors thank Nathan Post from the Wind Technology Testing Center (WTTC) of the National Renewable Energy Laboratory (NREL), and Larry Trentin from Massachusetts Clean Energy Center for providing a wind blade shell.

REFERENCES

- [1] Yazdanbakhsh, A., Bank, L. C., Chen, C., and Tian, Y., 2017, “FRP-Needles as Discrete Reinforcement in Concrete,” *Journal of Materials in Civil Engineering*, V. 29, No.10, pp.1-9.
- [2] Yazdanbakhsh, A., Bank, L. C., Rieder, K. A., Tian, Y., and Chen, C., 2018, “Concrete with discrete slender elements from mechanically recycled wind turbine blades,” *Resources, Conservation and Recycling*, V. 128, No. 07, pp. 11-21.
- [3] Osmani, M., and Pappu, A., 2010, “An assessment of the compressive strength of glass reinforced plastic waste filled concrete for potential applications in construction,” *Concrete Research Letters*, V.1, No.1, pp. 1-5.
- [4] Tittarelli, F, and Shah, S.P., 2013, “Effect of low dosages of waste GRP dust on fresh and hardened properties of mortars: Part 1,” *Construction and Building Materials*, V.47, pp. 1532-1538.
- [5] Correia, J. R., Almeida, N. M., and Figueira, J. R., 2011, “Recycling of FRP composites: Reusing fine GFRP waste in concrete mixtures,” *Journal of Cleaner Production*, V. 19, No.15, pp. 1745-1753.
- [6] Shahria Alam, M.; Slater, E.; and Muntasir Billah, A. H. M., 2013, “Green Concrete Made with RCA and FRP Scrap Aggregate: Fresh and Hardened Properties,” *Journal of Materials in Civil Engineering*, V. 25, No.12, pp. 1783-1794.
- [7] Yazdanbakhsh, A., Bank, L. C., and Chen, C., 2016, “Use of recycled FRP reinforcing bar in concrete as coarse aggregate and its impact on the mechanical properties of concrete,” *Construction and Building Materials*, V.121, pp. 278-284.
- [8] Bank, L. C., Yazdanbakhsh, A., Chen, C., and Tian, Y., 2016, “Reuse of Waste Gfrp Composites As Coarse Aggregates for Concrete.” *Proc., 8th International Conference on Fibre-Reinforced Polymer Composites in Civil Engineering*, CICE, Hong Kong, China, pp. 593-598.
- [9] Bank, L. C., and Yazdanbakhsh, A., 2016, “Concrete containing coarse aggregate recycled from scrap GFRP rebars,” *Proc., 6th International Conference on Structural Engineering, Mechanics and Computation - Insights and Innovations in Structural Engineering*, SEMC, Cape Town, South Africa, pp. 1410-1415.
- [10] ASTM C143/C143M., 2015, Standard Test Method for Slump of Hydraulic-Cement Concrete, West Conshohocken, PA.
- [11] ASTM C469/C469M., 2014, Standard Test Method for Static Modulus of Elasticity and Poisson’s Ratio of Concrete in Compression, West Conshohocken, PA.
- [12] ASTM C39, 2016, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, West Conshohocken, PA.
- [13] ASTM D2584-94, 2000, Standard Test Method for Ignition Loss of Cured Reinforce Resin, West Conshohocken, PA.

Mechanical Performance of Concrete Incorporating Slender Elements from Recycling GFRP Waste

Table 1- Properties of the GFRP rebar needles

Tensile strength, MPa (ksi)	620 – 896 (90 - 130)
Transverse shear strength, MPa(ksi)	150 (21.8)
Tensile modulus of elasticity, GPa(ksi)	46 (6672)
Specific gravity	1.96
24-h moisture absorption, %	Less than 0.25
Fiber content by weight, %	70
Fiber material	ECR glass fibers
Matrix material	Vinyl Ester resin

Table 2- Proportions of concrete mixture (kg/m³ concrete)

	1 st Series			2 nd Series				
Mixture	CTRL1	RB-5	RB-10	CTRL2	PLN-5	PLN-10	GRV-5	GRV-10
Cement	422	422	422	444	444	444	444	444
Water	190	190	190	216	216	216	216	216
Fine Agg. (SSD*)	683	683	683	632	632	632	632	632
Coarse Agg. (SSD*)	950	903	855	950	903	855	903	855
GFRP rebar needle	-	34	69	-	-	-	-	-
GFRP wind blade needle	-	-	-	-	34	69	34	69
Needle Vol Cont. (%)	-	1.76	3.52	-	1.76	3.52	1.76	3.52

* SSD represents saturated surface dry aggregate.

Table 3- Slump test results

Slump	CTRL 1	RB-5	RB-10	CTRL 2	PLN-5	PLN-10	GRV-5	GRV-10
mm	70	75	70	125	115	125	115	110

Table 4- Compressive strength (f_c), modulus of elasticity in compression (E) and splitting tensile strength (f_{ct}) test results and their mean value f_{cm} , E_m and f_{ctm} .

	f_c	f_{cm}	Change in f_{cm}	E	E_m	Change in E_m	f_{ct}	f_{ctm}	Change in f_{ctm}
Unit	MPa	MPa	%	GPa	GPa	%	MPa	MPa	%
CTRL1	41.3			29.1			3.46		
	39.1	40.2	-	24.2	29	-	3.86	3.42	-
	40.1			33.8			2.93		
GFRP-NDL-5	39.4			31.8			3.99		
	36.7	38	-5.47	29.6	30.7	5.86	4.64	4.18	22.22
	38			16.2*			3.9		
GFRP-NDL-10	36			42.0*			4.67		
	37.1	36.7	-8.71	35.5*	24	-17.24	3.66	4.55	33.04
	36.9			24			5.32		
CTRL2	36.1			24.7			2.65		
	36.7	36	-	27.4	25.9	-	3.68	3.35	-
	36.3			23.1			3.46		
	35			28.4			3.58		
PLN-5	33.2			29.2			2.98		
	36	35.5	-1.39	28	29.1	12.36	3.03	2.89	-13.73
	36			27.5			2.77		
	36.8			31.8			2.77		
PLN-10	35.6			29.2			3.1		
	35.1	36.1	0.28	26.8	27.4	5.79	3.76	3.35	0.00
	35.5			27.6			3.12		
	38.1			26			3.43		
GRV-5	38.8			26.6			2.93		
	38.9	38.6	7.22	26.9	27.6	6.56	2.67	2.91	-13.13
	37.5			31.6			3.1		
	39.2			25.4			2.94		
GRV-10	34.2			22.6			3.12		
	34.6	34.4	-4.44	23.6	24.7	-4.63	3.31	3.09	-7.76
	35.2			29.1			3.03		
	33.6			23.5			2.9		

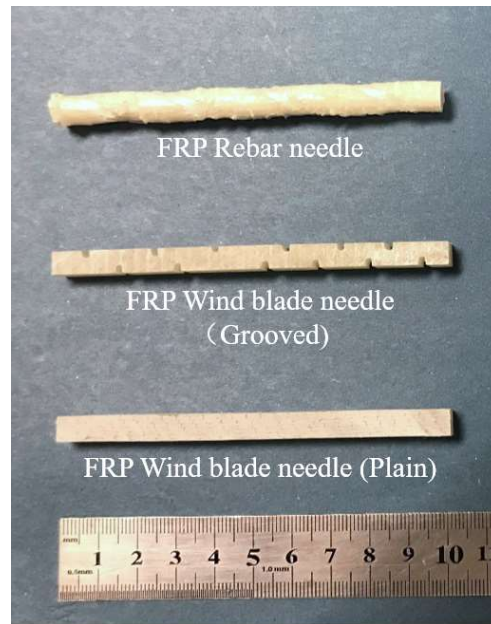


Figure 1- The recycled GFRP needles used in the concrete mixtures.



Figure 2- Representative Concrete specimens after splitting tensile strength tests in the first phase of the experiments, investigating rebar needles.

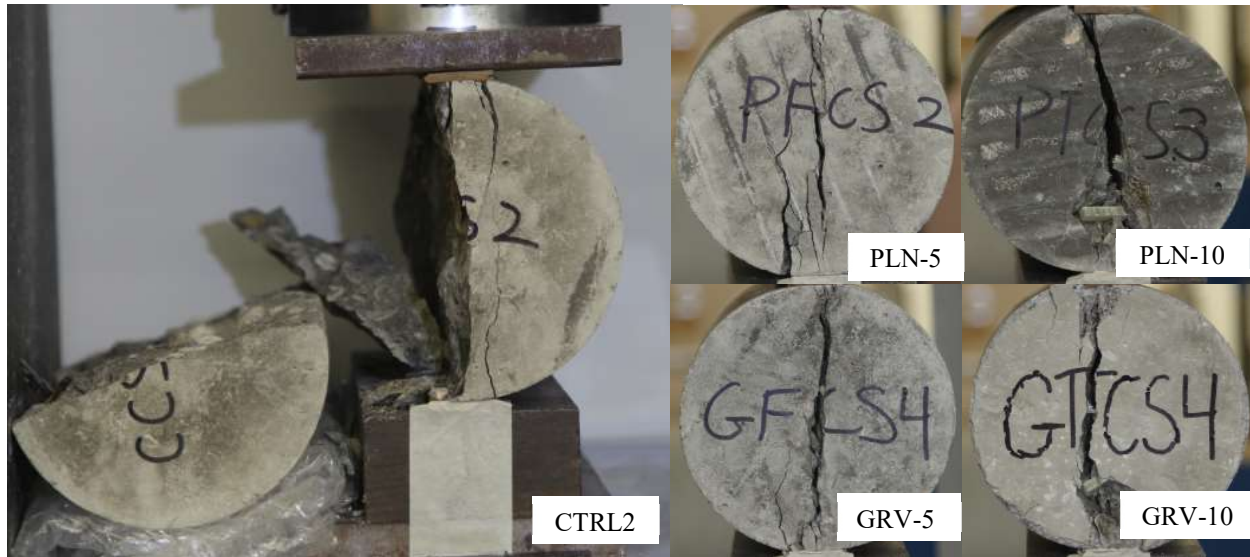


Figure 3- Representative concrete specimens after splitting tensile strength test in the second phase of experiments, investigating wind blade needles.

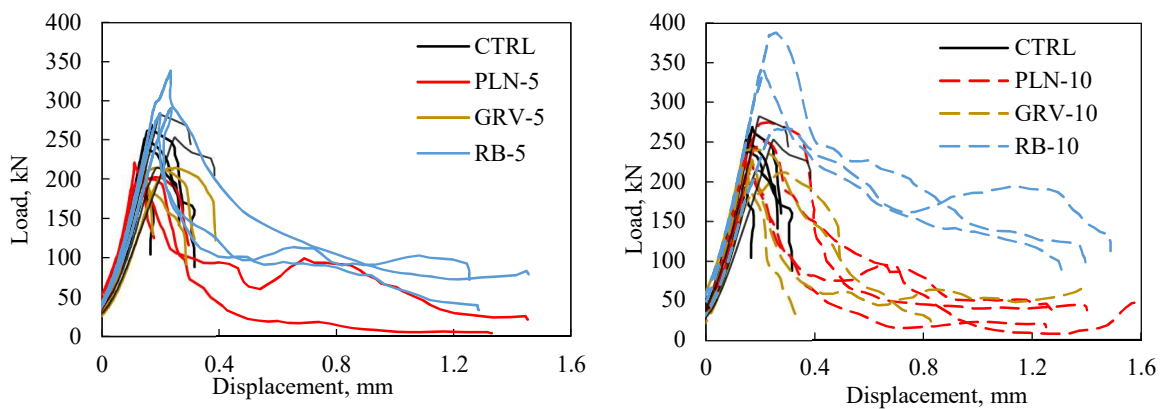


Figure 4- Load- displacement curves from splitting tensile strength testing of specimens in which (a) 5% and (b) 10% of coarse aggregate was volumetrically replaced with GFRP needles.



Figure 5— (a) GFRP rebar needles and (b) wind blade needles in representative specimens tested for measuring splitting tensile strength. The specimens were opened manually after the tests were completed. In both specimens, 10% of coarse aggregate is replaced by needles.

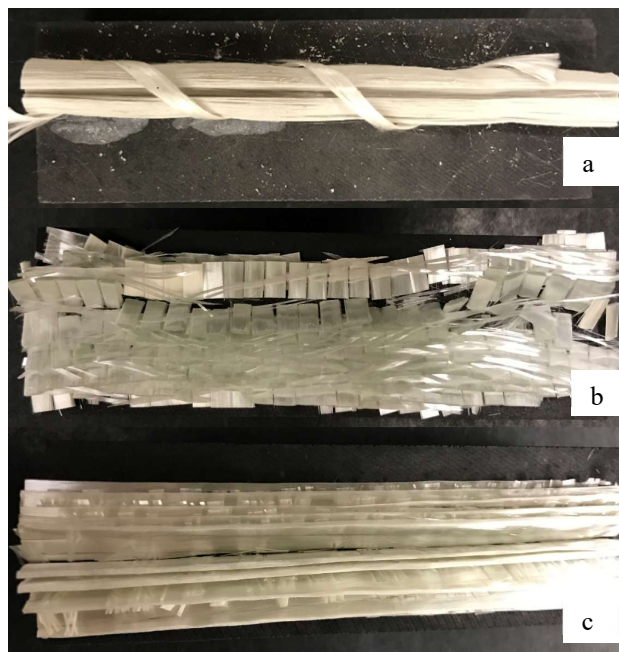


Figure 6— Specimens with burnt-off resin: (a) a GFRP rebar needle, (b) a wind blade needle with most of the glass fibers perpendicular to the needle axis, and (c) a wind blade needle with most of the glass fibers parallel to the needle axis.

Utilization of Reclaimed Asphalt Pavement Aggregates in Portland Cement Concrete for Concrete Pavement

Anol Mukhopadhyay and Xijun Shi

Synopsis: Potential issues associated with depletion of good aggregate sources and management of excess RAP stockpiles increasingly motivate use of RAP in PCC as a coarse aggregate replacement. Texas has shown great interest in disposing excess RAP stockpiles and a systematic study on using RAP in PCC for Texas pavement applications was conducted by the authors recently. This paper provides a concise summary of the findings from this study. The major conclusions are (1) PCC mixture with dense aggregate gradation can be achieved by adding coarse RAP with adequate intermediate sized particles, which offers better overall performance in terms of workability and mechanical properties, (2) RAP-PCC with coarse RAP replacement up to 40% showed considerable reduction for modulus of rupture. Asphalt cohesive failure (crack passing through the asphalt layer) was found to be the main mechanism responsible for the strength reductions, (3) the addition of allowable amounts of RAP into PCC provides equivalent durability performance relative to plain PCC, and (4) constructing pavements with RAP-PCC yields economic, environmental and social benefits.

Keywords: reclaimed asphalt pavement, portland cement concrete, microstructure, durability, life cycle assessment

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INTRODUCTION

Aggregate cost often comprises 20-30% of the material cost in concrete pavement. Some concern has been raised that the days of having unlimited supplies of high quality virgin aggregates for concrete paving have gone [1]. Many of the good aggregate sources become scarce, resulting in a continuous increase in aggregate cost. The increase in aggregate cost is largely due to higher energy consumption during aggregate production and transportation together with higher expense to regulate environment related issues [1]. Accordingly, contractors have been increasingly motivated to use recycled aggregate materials such as recycled concrete aggregate (RCA) and reclaimed asphalt pavement (RAP) to produce portland cement concrete (PCC). Lab based research on the use of RAP to make PCC probably dates back to 1970s, followed by considerable amounts of efforts around the world in the past 40 years [2-17]. A recently growing interest in exploring alternative ways to use RAP has already motivated several state Departments of Transportation (DOTs) and Toll Highway Authorities to financially support projects related to use of RAP in making PCC [11-14, 18, 19]. On the other hand, the increasing maintenance and rehabilitation actions of hot mix asphalt (HMA) pavement along with the limited use of RAP in making new HMA generate excess RAP in some states. According to a survey, the possession of excess RAP has been reported by 91% of U.S contractors [20]. The expanding RAP stockpiling not only consumes more space and money, but also poses a threat to both environment and public safety. A successful use of RAP in PCC saves money in purchasing and transporting virgin aggregate and reduces pollution related to mining and production and consumption of virgin aggregates; it also facilitates disposing excess RAP and avoids the issues caused by RAP stockpiling.

Building a sustainable infrastructure system has always been one of strategic priorities for the Texas Department of Transportation (TxDOT). TxDOT's interest on disposing excess RAP stockpiles was reflected in sponsoring a research project on utilization of RAP in making PCC three years back and Texas A&M Transportation Institute (TTI) was awarded this project. This

paper provides a concise summary of the findings from this recently completed research project [14, 19].

MATERIALS AND METHODOLOGY

Four coarse RAPs collected from four districts (RAP ID: HOU, AMA, BRY and SA) under TxDOT were systematically characterized in the lab. Pictures of the RAP samples are shown in Figure 1. It is noted that the occurrence of agglomerated particles (i.e. adherence of multiple particles due to sticky asphalt) is commonly observed in both HOU and AMA RAPs (more in AMA than HOU), while particles of SA and BRY RAPs are generally loose and clean.

The gradations of the RAP materials are shown in Figure 2 in comparison with the virgin aggregates used in this study. From Figure 2, the gradations of the HOU and AMA RAPs are similar to #57 coarse aggregate gradation (ASTM C 33), and both of these coarse RAPs show presence of higher quantity of fraction between 25.4 mm and 9.5 mm. The BRY RAP is the least processed RAP source containing particles of coarse (retaining on 9.5 mm sieve), intermediate (passing 9.5 mm sieve and retaining on 2.36 mm sieve) and fine (passing 2.36 mm sieve) size ranges. A 2.36 mm size sieve was used to reject fine particles (<2.36mm) and obtain sample with coarse and intermediate size particles for the BRY RAP. The SA RAP contains mostly the particles within the size range between 2.36 mm and 9.5 mm, which means that most of the SA RAP particles are intermediate sized. The results of material characterization of the aggregate materials are shown in Table 1. According to Table 1, the RAP aggregates have lower dry unit weight, specific gravity, and absorption compared to the virgin coarse aggregate. A detailed discussion of the material characterization results can be found in [21].

A series of RAP-PCC mixtures according to TxDOT's Class P (paving) concrete specification [22] were formulated with up to 40% volumetric replacement of coarse virgin aggregate by coarse RAP. The 40% RAP replacement level limit was determined from several previously published investigations [12, 14]; those investigations indicated that higher than 50% RAP replacement levels would cause high strength and modulus reductions which may not be used for pavement applications. Fine RAP was not used in these mixes because fine RAP causes significant strength reduction [8, 13, 14] and workability issues [8, 14] in RAP-PCC. Moreover, high asphalt content of fine RAP can be economically used to make HMA. The mix design of the studied mixtures is shown in Table 2.

Various aspects including mechanical properties, microstructures and crack pattern, durability, and life cycle assessment related to the use of RAP-PCC in pavement applications were evaluated through robust experimental, analytical and, simulation approaches. The aims and methodology of each aspect are summarized in Table 3.

RESULTS AND ANALYSIS

Effect of RAP on PCC Properties

The mechanical properties of RAP-PCC mixtures were extensively studied in the past. The findings from the current study matches well with the previous findings using coarse RAP to make PCC: (i) adding RAP into PCC caused reductions in strengths (e.g., 20-47% for 28-day compressive strength when 40% RAP was added ; 11-24% for 28-day modulus of rupture when 40% RAP was added) and modulus of elasticity (21-27% for 28-day modulus of elasticity when

40% RAP was added) [14, 21], and (ii) reduction in flexural strength was always lower than that in compressive strength irrespective of coarse RAP replacement levels [11, 14, 21]. The most critical RAP aggregate properties that affect RAP-PCC properties are gradation, percent agglomerated particles, and asphalt content. Coarse RAP with suitable gradation with well separated particles and containing sufficient intermediate size particles (such as BRY and SA RAPs) were successfully used to achieve dense-graded RAP-PCC in this study. The dense-graded RAP-PCC mixtures using BRY and SA RAPs showed better workability and less reduction in mechanical properties compared to the gap-graded RAP-PCC mixtures using HOU and AMA RAPs. The agglomerated RAP particles create weak zones in the RAP-PCC system. It is interesting to note that AMA contains the highest amount of agglomerated particles and the RAP-PCC mixtures containing AMA RAP yielded highest strength reductions.

The development of guidelines and recommendations for designing RAP-PCC paving mixtures that satisfy concrete paving material strength requirements was conducted in this study and published earlier [19]. An innovative method using the relationship/trend between the total asphalt volumetric fraction (TAVF) and strength to determine the optimum RAP replacement level in a RAP-PCC mixture was also developed and published earlier [21]. The TAVF was defined as the volume fraction of the asphalt in the total aggregate mixture (virgin aggregates plus RAP aggregates); it showed a strong linear relationship with the RAP-PCC strengths within the studied range. This means the higher the asphalt content the higher is the strength (compressive and flexural) reduction in general. Because the asphalt was found to be the weak zone in RAP-PCC system (discussed later), using asphalt content (e.g., TAVF) as a control parameter to predict mixture strengths and subsequently, to determine optimum RAP replacement level turns out to be very effective. An extensive description of the procedures to determine the optimum RAP replacement level can be found in the authors' previous publication [21]. The slope (k) of the strength vs. TAVF curve is defined as the rate of deterioration, representing how fast the addition of a particular RAP material negatively affects the strength reduction. It is found that the dense-graded RAP-PCC mixtures using BRY or SA RAPs had a lower k value relative to that of the gap-graded RAP-PCC mixtures using HOU or AMA RAPs (Figure 3). It is hypothesized that k is a function of asphalt content (function of asphalt content and replacement level of RAP) and combined aggregate gradation (dense vs gap gradation) contributed by the RAP in RAP-PCC mix along with some influence by % agglomerated RAP particles (higher % of agglomerated RAP particles enhances strength reduction).

RAP-PCC microstructures and crack pattern

A comprehensive investigation on microstructural characterization and crack propagation of RAP-PCC through a combined approach by using thin section based petrographic method, scanning electron microscope (SEM) and X-ray CT was conducted. Thin section study under transmitted light optical microscope was very effective to characterize relevant micro-structural features of RAP-PCC (e.g., nature of crack propagation, overall interfacial transition zone (ITZ) information, air void distribution and quantification etc.) using sample covering large surface area (55 × 75 mm). The SEM-EDS was used for a detailed characterization of ITZ (e.g., nature of distribution of pores and CH) using fractured surface sample with small dimension (10 to 15mm) covering micro to nano-scale. A high resolution (~ 53 μ m voxel size with 50 mm dia. specimen) X-ray CT was found to be very effective to not only validate the features obtained from petrography and SEM-EDS but also provide an extensive analysis of multiple features such as air void distribution

and quantification, and crack propagation. The major findings of the microstructure and crack pattern study are summarized below:

1. The presence of fine aggregate is invariably observed within the asphalt layer around RAP particle (Figure 4.a) for all the studied RAP-PCC samples, which causes increase in thickness and porosity of the asphalt layers at places. The presence of fine aggregates and pores makes asphalt layer weak and crack can easily pass through it. As a result, asphalt cohesive failure (i.e., crack passing through the asphalt layer, Figure 4.b and 4.c) was found to be the main cause of reduction in strength and modulus in the studied RAP-PCC mixtures.
2. The presence of agglomerated RAP particles with varying proportions is commonly observed in all the studied RAP materials under microscope, despite that some of these agglomerated particles appear to be a single particle in naked eye. Adherence of multiple RAP particles through asphalt films (the degree of adherence varies with the viscosity of asphalt film, which is a function of asphalt age and ambient temperature) is the main reason of forming agglomerated particles. The non-separated agglomerated RAP particles (survived during mixing) in RAP-PCC are easily identifiable under the microscopic observation (Figure 5.a). Because of the presence of thick porous asphalt layer within and around these agglomerated particles (Figures 5a and 5b), weak zones are created wherever agglomerated particles occur in RAP-PCC. Crack easily passes through these agglomerated particles (Figures 5b and 5c) and this also causes reduction in strength and modulus in RAP-PCC.
3. The introduction of RAP into PCC yields porous interfacial transition zone (ITZ) around RAP particles (Figure 6.a). The presence of asphalt layer in RAP has some effect on CH crystallization in the ITZ. It seems the presence of asphalt layer around RAP particles makes CH crystals in the ITZ area between RAP and cement paste smaller in size and less in number (Figure 6.b). It appears that porous nature of ITZ around RAP particles impact negatively whereas CH characteristics in the ITZ impact positively on strength development on RAP-PCC. As crack easily passes through the asphalt layer in RAP-PCC (i.e., cohesive failure), the porous nature of ITZ may have less negative impact in RAP-PCC performance compared to the reference concrete.
4. The PCC sample containing 100% coarse and fine RAP replacements (defined as 0.40_520_100BRY/100BRY) exhibits greater amounts of air voids compared to the control PCC samples both from thin section based petrographic study (Figure 7.a) and from X-ray microscope analysis [14]. In the samples with 100% RAP replacement, the increase of porosity both in ITZ as well as CPM has been observed (Figure 7.b), which makes the mixture more vulnerable to crack. This indicates that higher level of RAP replacement (> 40-50%) may cause relatively higher air content with possibly non-favorable air void distribution in RAP-PCC mixes.

In summary, the reduction of strengths and modulus in RAP-PCC might be caused by a combined effect of (i) presence of thin and porous asphalt layer around RAP aggregates at places – crack easily passes through the asphalt layer, (ii) presence of agglomerated RAP particles with varying proportions – agglomerated particles are the weak spots in RAP-PCC and crack easily passes through these particles, (iii) the effect of higher overall porosity both in ITZ and cement paste matrix has some role on strength reduction but might not be very significant.

RAP-PCC durability

Concrete durability, defined as concrete's resistance to weathering action, chemical attack, abrasion and other degradation processes by the American Concrete Institute (ACI), is an indispensable aspect to ensure pavement's long-term performance. A PCC slab designed with permissible mechanical properties can be easily deteriorated if it does not have adequate durability. The durability might be especially important for RAP-PCC because RAP is a recycled material which already suffered from a long period of asphalt degradation process in the field. While considerable amount of data is available for the RAP-PCC mechanical properties, the durability of RAP-PCC has not yet been comprehensively investigated. Based on previous limited durability related lab test results, RAP-PCC exhibited no significant reductions in durability such as freeze-thaw resistance, chloride permeability, abrasion resistance and shrinkage [12, 13]. The current study expanded the RAP-PCC durability database by generating similar durability test results along with some additional testing for the studied RAP-PCC mixtures. The major findings are:

1. The durability factors of all the RAP-PCC mixtures as well as the control mixture did not drop below the limiting value of 60 after 300 freeze/thaw cycles according to ASTM C666, suggesting all the mixtures had adequate freeze-thaw resistance.
2. Based on the 28-day bulk electrical resistivity of saturated concrete, all the samples (RAP-PCC mixtures and control mixture) were rated as low chloride penetration level.
3. The abrasion resistance of RAP-PCC appeared be adequate, although the RAP-PCC samples generally showed slightly higher wear depth values, the difference was not considerable

Based on the findings from this study as well as the conclusions from the existing publications, in general, the RAP-PCC can have adequate durability in term of freeze-thaw resistance, permeability, and abrasion resistance. It is highly recommended to generate additional testing results with PCC containing RAP from a wide range of RAP sources to verify these findings. The field section-based study to verify long term durability of RAP-PCC system is also an important aspect as further research.

Life cycle assessment of RAP-PCC pavements

Because the RAP-PCC pavement was rarely implemented in the field in the past, the evaluation of RAP-PCC pavement performance is challenging, and further work is highly warranted. The authors have conducted some work related to RAP-PCC pavement performances using conventional rigid pavement design tool such as AASHTO 1993, TxCRCP-ME, and Pavement ME [14, 23]. From the authors' study, use of the TxDOT conventional pavement design tools (i.e., AASHTO 1993 and TxCRCP ME) yielded a slightly higher slab thickness for single lift pavement containing RAP-PCC relative to control pavement. However, the Pavement ME predictions indicated that RAP-PCC's lower modulus of elasticity could be beneficial. By using existing models for Pavement ME simulation, the authors found that CRCP slab with lower modulus tends to develop tighter transverse cracks. The tighter transverse cracks would have better load transfer capability, which ultimately causes pavement to have longer service life [23, 24]. Furthermore, it has been shown from some existing publications that the RAP-PCC has improved ductility, fracture properties, and toughness [12, 23, 25]. These improved properties are likely to have positive effects on pavement performance as well.

Three pavement structures with similar performances were determined through proper justifications [26]. The three pavement structures are (i) Single-lift plain PCC pavement, (ii)

single-lift RAP-PCC pavement, and (iii) two-lift concrete pavement with RAP-PCC as bottom lift, which are shown in Figure 8.

A life cycle inventory analysis case study using the aforementioned three pavement structures is presented in this section in order to quantify the potential economic, social, and environmental benefits of using RAP in PCC for pavement applications. A complete summary of % change for the pavements containing RAP-PCC relative to the single-lift plain PCC pavement in the life cycle inventory analysis is presented in Table 4. The % change is defined as:

$$\% \text{ change} = \frac{\text{impact of RAP PCC pavement} - \text{impact of the plain PCC pavement}}{\text{impact of the plain PCC pavement}} \times 100 \quad (1)$$

A negative value of % change means that the pavement containing RAP-PCC reduces the economic, social or environmental burden in the material manufacturing and pavement construction stage. Table 4 suggests that the RAP-PCC pavements benefit most aspects, which is primarily due to the less consumption of virgin aggregates, less virgin aggregates transported to the plant, less RAP transported to the landfill site, and less RAP being landfilled. However, the increased slab thickness of the single-lift RAP-PCC pavement requires higher amounts of raw material. The higher amounts of material consumption (especially the cement consumption) can have negative effects on some of the categories such as global warming potential, SO₂ release, greenhouse gasses emission, and toxic releases. For the two-lift concrete pavement using RAP-PCC in the bottom lift, the increased construction cost as well as the higher cement content in the top lift reduces the sustainable benefits resulted from RAP recycling in the bottom lift. All in all, the use of RAP-PCC for pavement applications could still yield considerable economic, social, and environmental benefits, so this strategy should be highly encouraged. It is concluded in this case study that the single-lift RAP-PCC pavement could yield the highest economic benefits, while the two-lift concrete pavement could have highest positive impact from social and environmental perspective.

CONCLUSIONS

RAP-PCC is a construction material which meets the increasing need for sustainability and therefore should be greatly advocated. It is feasible to use RAP-PCC material to construct single-lift pavement with up to 40-50% coarse RAP replacement level under current TxDOT's strength based specifications. The idea of using RAP-PCC as a bottom lift in a two-lift PCC pavement provides an alternative way to maximize the RAP usage without compromising the pavement performance. A systematic study on RAP-PCC covering various aspects was conducted by the authors. The major findings from this study are:

1. RAP-PCC mixtures with optimized aggregate gradation can be achieved with the addition of coarse RAP with sufficient amounts of intermediate sized particles. Dense graded RAP-PCC showed better overall performance in terms of workability, mechanical properties, and durability.
2. Adding RAP into PCC results in porous ITZ and higher overall porosity. However, the effects on size and nature of distribution of CH crystals in the ITZ are negligible.

3. Asphalt cohesive failure is the primary mechanism responsible for reductions in strengths in RAP-PCC. High amounts of total porosity and the porous nature of ITZ play a secondary role on crack propagation and are less critical.
4. The addition of allowable amounts of RAP into PCC does not cause significant reductions in concrete durability in terms of freeze-thaw, shrinkage, permeability, etc.
5. Constructing pavements with RAP-PCC material yields economic, environmental and social benefits. Such benefits for a two-lift RAP-PCC pavement can be further increased if the paving cost for a two-lift construction is reduced.

The RAP usage is anticipated to be increased once a fracture properties based pavement design is established. The important future work is to generate more lab and field data to verify that RAP-PCC has adequate durability and surface characteristics. Besides, research to develop a fracture based material criterion for applying on RAP-PCC pavements is highly warranted.

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References

- [1] J. Hu, M.S. Siddiqui, P. David Whitney, Two-lift concrete paving—case studies and reviews from sustainability, cost effectiveness and construction perspectives, TRB 93rd Annual Meeting Compendium of Papers, 2014.
- [2] V. Patankar, R. Williams, Bitumen in dry lean concrete, Highways and Traffic Engineering (1970).
- [3] S. Kolias, Mechanical properties of cement-treated mixtures of milled bituminous concrete and crushed aggregates, Materials and Structures 29(7) (1996) 411-417.
- [4] M. Delwar, M. Fahmy, R. Taha, Use of reclaimed asphalt pavement as an aggregate in Portland cement concrete, ACI Materials Journal 94(3) (1997).
- [5] I. Dumitru, G. Smorchevsky, V. Caprar, Trends in the utilisation of recycled materials and by-products in the concrete industry in Australia, Proc. of the Concrete Institute of Australia 19th Biennial Conf., Sydney, 1999, pp. 289-301.
- [6] K. Hassan, J. Brooks, M. Erdman, The use of reclaimed asphalt pavement (RAP) aggregates in concrete, Waste Management Series 1 (2000) 121-128.
- [7] V. Mathias, T. Sedran, F. de Larrard, Recycling reclaimed asphalt pavement in concrete roads, PRO 40: International RILEM Conference on the Use of Recycled Materials in Buildings and Structures (Volume 1), RILEM Publications, 2004, p. 66.
- [8] B. Huang, X. Shu, G. Li, Laboratory investigation of portland cement concrete containing recycled asphalt pavements, Cement and Concrete Research 35(10) (2005) 2008-2013.
- [9] S. Al-Oraimi, H.F. Hassan, A. Hago, Recycling of reclaimed asphalt pavement in portland cement concrete, The Journal of Engineering Research 6(1) (2009) 37-45.
- [10] F.O. Okafor, Performance of recycled asphalt pavement as coarse aggregate in concrete, Leonardo Electronic Journal of Practices and Technologies 9(17) (2010) 47-58.
- [11] M. Tia, N. Hossiney, Y.-M. Su, Y. Chen, T.A. Do, Use of reclaimed asphalt pavement in concrete pavement slabs, Report 00088115, U.S. Dep. of Transportation, Florida, 2012.
- [12] A.S. Brand, J.R. Roesler, I.L. Al-Qadi, P. Shangguan, Fractionated reclaimed asphalt pavement (FRAP) as a coarse aggregate replacement in a ternary blended concrete pavement, Report ICT-12-008, Illinois State Toll Highway Authority, Downers Grove, 2012.
- [13] M. Berry, J. Stephens, B. Bermel, A. Hagel, D. Schroeder, Feasibility of reclaimed asphalt pavement as aggregate in portland cement concrete pavement, Report FHWA/MT-13-009/8207, U.S. Dep. of Transportation, Montana. 2013.
- [14] A. Mukhopadhyay, X. Shi, Validation of RAP and/or RAS in hydraulic cement concrete: technical report, Report FHWA/TX-17/0-6855-1, U.S. Dep. of Transportation, Texas, 2017.
- [15] S. Singh, G. Ransinchung, P. Kumar, Feasibility study of RAP aggregates in cement concrete pavements, Road Materials and Pavement Design (2017) 1-20.
- [16] S. Singh, G. Ransinchung, P. Kumar, Effect of mineral admixtures on fresh, mechanical and durability properties of RAP inclusive concrete, Construction and Building Materials 156 (2017) 19-27.
- [17] S. Singh, S. Debbarma, P. Kumar, Utilization of reclaimed asphalt pavement aggregates containing waste from Sugarcane Mill for production of concrete mixes, Journal of Cleaner Production 174 (2017) 42-52.
- [18] M. Berry, K. Dalton, F. Murray, Feasibility of reclaimed asphalt pavement as aggregate in portland cement concrete pavement phase II: field demonstration, Report FHWA/MT-15-003/8207, U.S. Dep. of Transportation, Montana, 2015.

- [19] A. Mukhopadhyay, X. Shi, Validation of RAP and/or RAS in hydraulic cement concrete: guidelines and implementation recommendations, Report FHWA/TX-17/0-6855-P1, U.S. Dep. of Transportation, Texas, 2017.
- [20] K.R. Hansen, A. Copeland, Asphalt pavement industry survey on recycled materials and warm-mix asphalt usage: 2014, Report IS-138, National Asphalt Pavement Association, Lanham, MD. 2015.
- [21] X. Shi, A. Mukhopadhyay, K.-W. Liu, Mix design formulation and evaluation of portland cement concrete paving mixtures containing reclaimed asphalt pavement, Construction and Building Materials 152 (2017) 756-768.
- [22] TxDOT, Standard specifications for construction and maintenance of highways, streets, and bridges, Texas Department of Transportation, Austin, Texas, 2014.
- [23] X. Shi, Evaluation of portland cement concrete containing reclaimed asphalt pavement for pavement applications, PhD dissertation, Texas A&M University, College Station, Texas, 2018.
- [24] X. Shi, D.G. Zollinger, A. Mukhopadhyay, Punchout study for continuously reinforced concrete pavement containing reclaimed asphalt pavement using pavement ME models, International Journal of Pavement Engineering (2018) 1-14.
- [25] X. Shi, M. Mirsayar, A.K. Mukhopadhyay, D.G. Zollinger, Characterization of Two-Parameter Fracture Properties of Portland Cement Concrete Containing Reclaimed Asphalt Pavement Aggregates by Semicircular Bending Specimens, Cement Concrete Composites 95 (2019) 56-69.
- [26] X. Shi, A. Mukhopadhyay, D.G. Zollinger, Sustainability assessment for portland cement concrete pavement containing reclaimed asphalt pavement aggregates, Journal of Cleaner Production 192 (2018) 569-581.

Table 1 Material characterization

RAP/ Aggregate ID	Description	Stone type	Asphalt content (%)	Dry unit weight (kg/ m³)	Oven dry specific gravity	Absorption (%)
CA	Virgin coarse aggregate, a limestone aggregate with #4 (#57 in ASTM C 33) gradation	Limestone with minor chert particles	na	1551	2.51	2.79
FA	Virgin fine aggregate, a natural siliceous concrete sand	Siliceous river sand	na	-	2.58	2.06
HOU	Coarse RAP collected from Houston district, Texas	Gravel made of mostly limestone with some siliceous particles	4.00	1335	2.41	2.61
AMA	Coarse RAP collected from Amarillo district, Texas	Siliceous Gravel (quartzitic)	5.25	1255	2.40	1.89
BRY	Unfractionated RAP collected from Bryan district, Texas	Limestone with few siliceous particles (minor phase)	6.19	1373	2.36	1.78
SA	Coarse RAP collected from San Antonio district, Texas	Limestone	4.62	1425	2.33	2.69

Table 2 Mix design

Materials	0.40_520_40 REF	0.40_520_20 HOU	0.40_520_40 HOU	0.40_520_20 AMA	0.40_520_40 AMA	0.40_520_20 BRY	0.40_520_40 BRY	0.40_520_20 SA	0.40_520_40 SA
Cement (kg/m ³)	247	247	247	247	247	247	247	247	247
Fly ash (kg/m ³)	62	62	62	62	62	62	62	62	62
Virgin coarse aggregate (kg/m ³)	1058	825	604	842	628	830	611	846	635
Coarse RAP (kg/m ³)	0	206	403	202	400	208	408	196	393
Virgin fine aggregate (kg/m ³)	769	787	804	775	781	776	783	768	768
Water reducer (ml/m ³)	402	402	402	402	402	402	402	402	402
Air entraining agent (ml/m ³)	60	60	60	60	60	60	60	60	60
Water (kg/m ³)	123	123	123	123	123	123	123	123	123

Note: The mixture code used the following format: w/cm_cementitious content_replacement level+RAP type. Example: 0.40_520_40HOU represents a mix that has 0.40 w/cm ratio, 520 lb/cy (309 kg/m³) cementitious content, and made of HOU RAP with 40% replacement level.

Table 3 Aims and methodology for different aspects of this research

Aspects	Aims & methodology
Mechanical properties	• Validate the previously published findings on mechanical properties (i.e., compressive strength, modulus of elasticity, flexural strength and, splitting tensile) of RAP-PCC • Develop an effective approach to determine the optimum RAP replacement level the trend of global asphalt volumetric fraction vs strength
Microstructures and better understanding on the mechanisms of strength reduction	• Investigate the effect of RAP on PCC's microstructures through the application of conventional petrographic techniques as well as some advanced micro-analytical techniques such as X-ray CT and SEM imaging and analysis • Study the crack pattern and propagation using thin section based petrographic and X-ray CT techniques and understand the failure mechanisms during strength testing for RAP-PCC
Durability	• Verify RAP-PCC has adequate durability by performing relevant durability tests including freeze-thaw resistance, permeability, and abrasion resistance tests.
Life cycle assessment	• Documenting the benefits of using RAP in making PCC in terms of measuring all three aspects of sustainability (i.e., economic, social and environmental) through an Economic Input-Output Life Cycle Assessment

Table 4 EIO-LCA results

Impact	Assessment	Type	% change for the pavements containing RAP-PCC relative to single-lift plain PCC pavement	
			Single-lift RAP-PCC pavement	Two-lift concrete pavement
Economic impact	Total economic	Total economic	-10.90	-6.92
Social impact	Transportation movement	Transportation movement	1.05	-3.38
	Land use	Land use	-8.14	1.16
	Energy use	Total	-1.25	-4.13
		Coal	7.53	1.51
		Natural Gases	-1.52	-3.47
		Petroleum-based fuel	-13.86	-12.73
		Biomass/waste fuel	7.95	2.27
		31% non-fossil fuel electricity	2.06	-1.90
	TRACI impact assessment	Global warming potential	3.00	-1.20
		Ecotoxicity (air)	-3.16	-6.33
		Ecotoxicity (water)	-3.02	-2.26
		Smog	-3.05	-6.21
		Human health cancer	-4.25	-5.42
		Human health noncancer	-37.87	-27.07
Environmental impact	Conventional air pollutants	Total	-3.81	-2.42
		CO	-5.05	-6.14
		NH ₃	-5.24	-4.19
		NO _x	-3.13	-6.25
		PM ₁₀	-11.52	-11.52
		PM _{2.5}	-7.55	-9.34
		SO ₂	6.03	0.50
		VOC	-9.94	-9.29
	Greenhouse gases emissions	Total	3.00	-1.30
		CO ₂ fossil	-0.72	-3.97
		CO ₂ process	9.50	2.85
		CH ₄	-21.61	-16.95
		N ₂ O	-5.11	-0.57
		HFC/PFCs	-1.27	-0.64
	Toxic releases	Total	2.60	-0.23
		Fugitive air	-5.08	-1.69
		Stack	6.68	1.47
		Total air	6.28	1.57
		Surface water	-2.31	-1.65
		Underground water	-10.68	-7.12
		Land	-3.69	-3.45
		Off-site	-12.82	-6.30



Figure 1 Pictures of the studied RAP materials

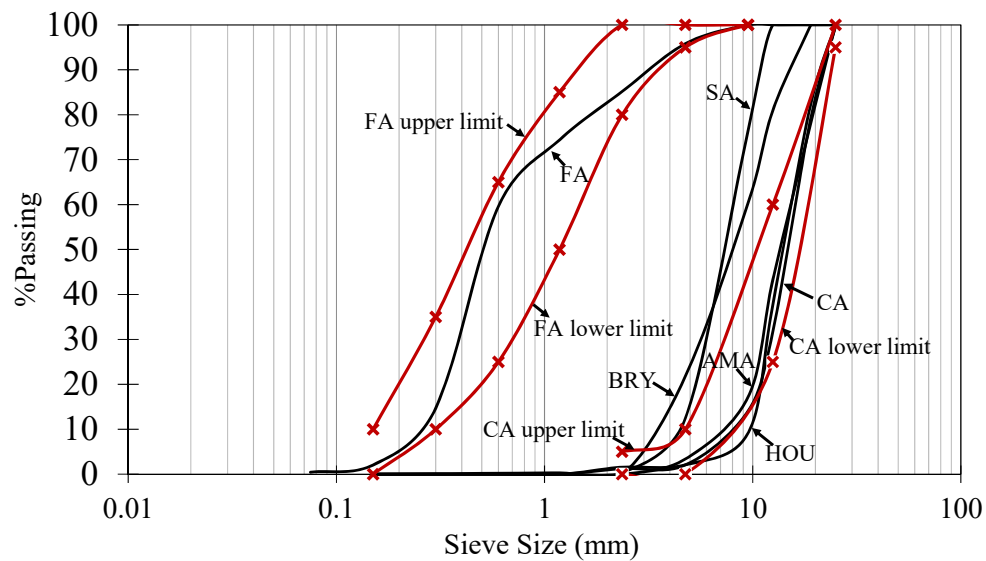


Figure 2 Gradations of the aggregate materials

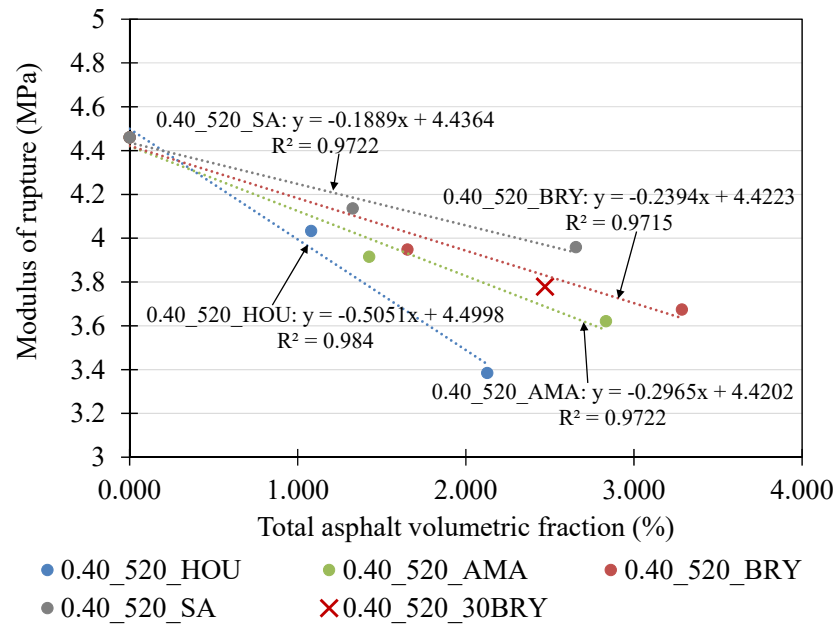


Figure 3 Correlation between asphalt fraction and modulus of rupture [21]

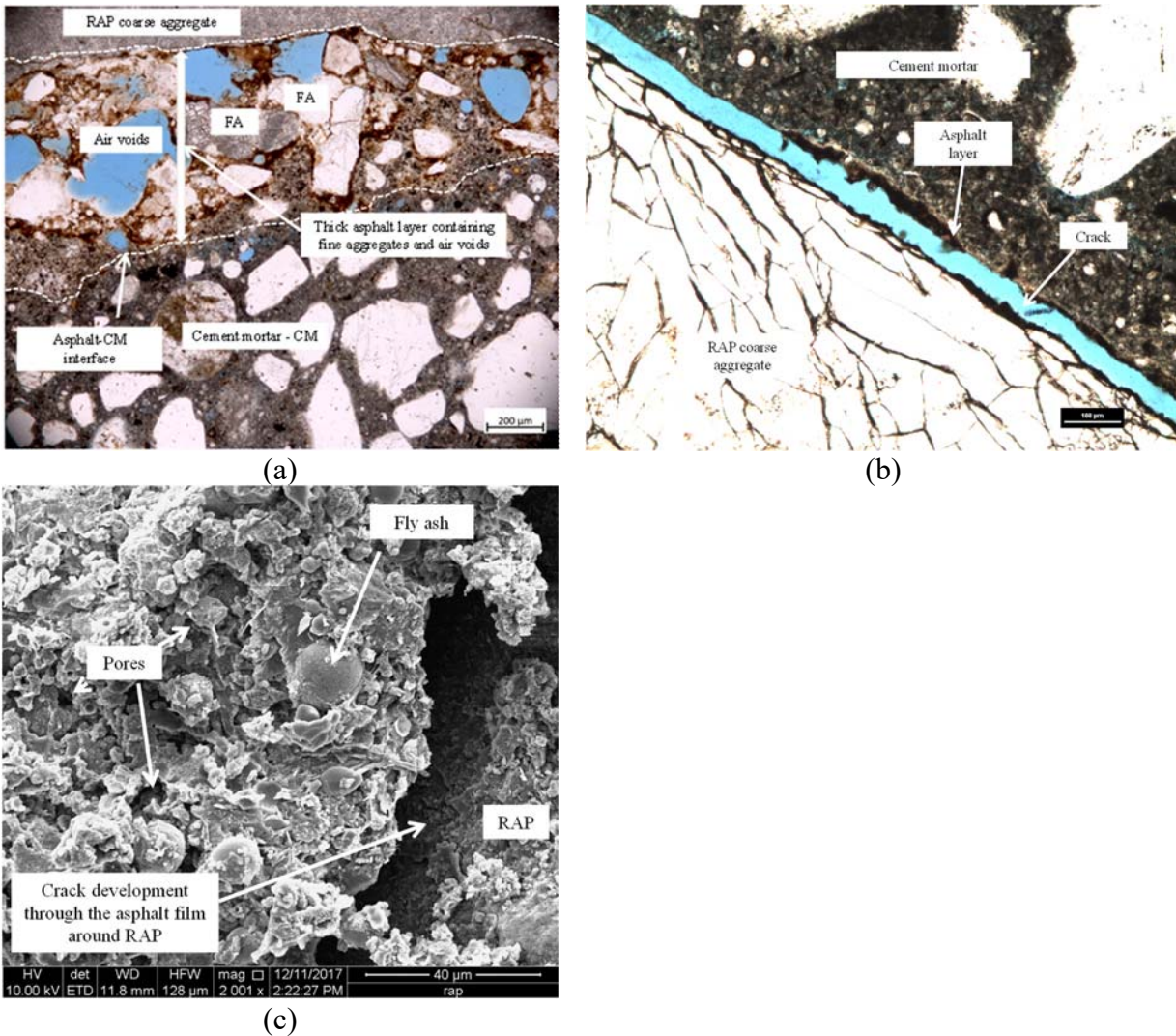


Figure 4 Nature of asphalt layer and crack propagation: (a) a view of the asphalt layer containing air voids and fine aggregates (0.40_520_40BRY, thin section (TH), transmitted light optical microscope (TLOM); (b) an example of asphalt cohesive failure, i.e., crack passing through the asphalt layer in 0.40_520_40HOU, TH, TLOM; (c) crack development through the asphalt layer around RAP in 0.40_520_40BRY, observed under secondary mode SEM. FA-Fine Aggregate.

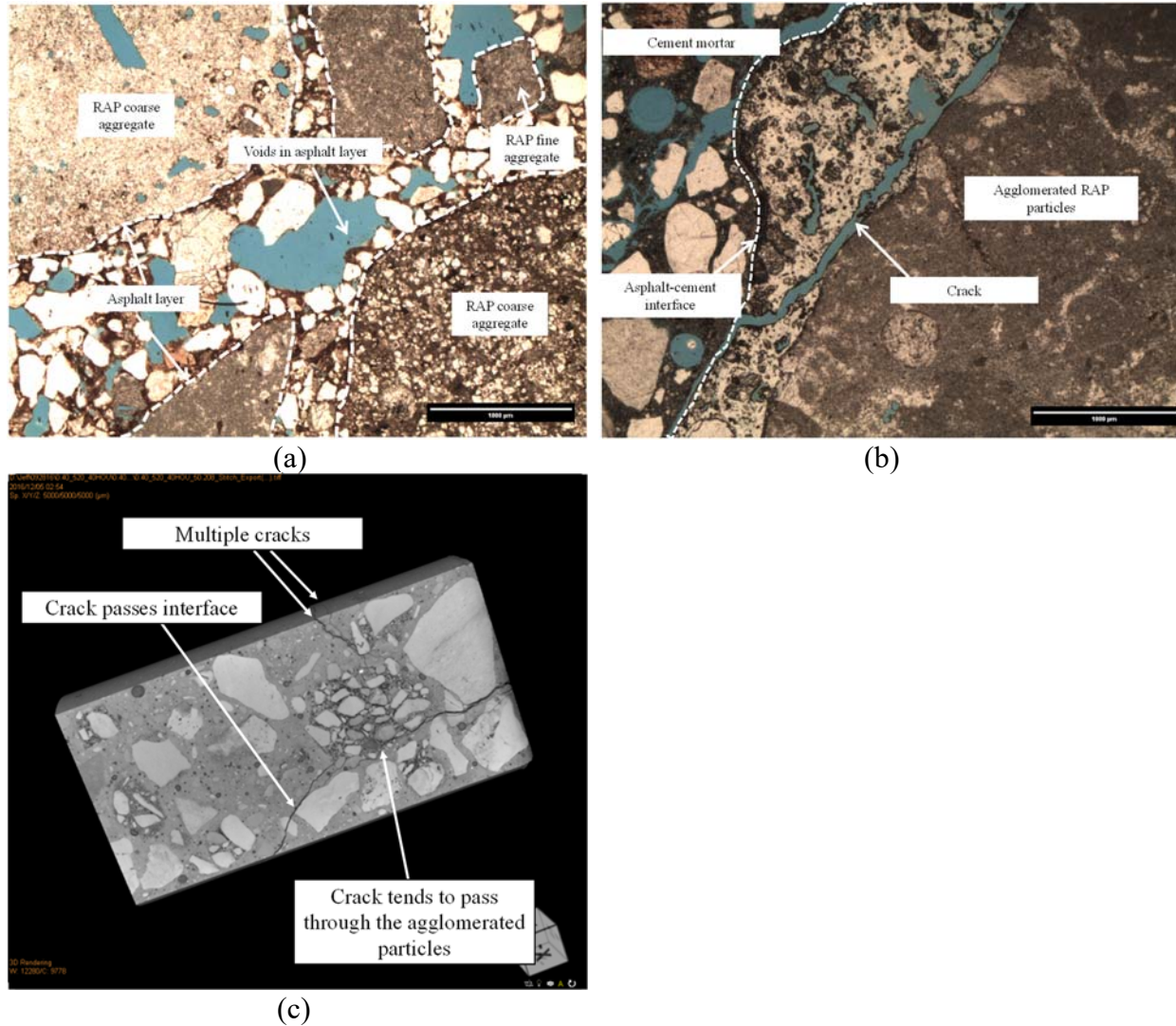


Figure 5 The presence of agglomerated RAP particles and crack propagation: (a) agglomerated RAP particles in the RAP-PCC sample 0.40_520_40HOU, TH, TLOM, (b) crack passes through the agglomerated RAP particle in sample 0.40_520_40BRY, TH, TLOM, and (c) crack passes through the agglomerated RAP particle in sample 0.40_520_40HOU, an X-Ray CT 3D image. The scale bar in Figure (a) and (b) represents 1000µm.

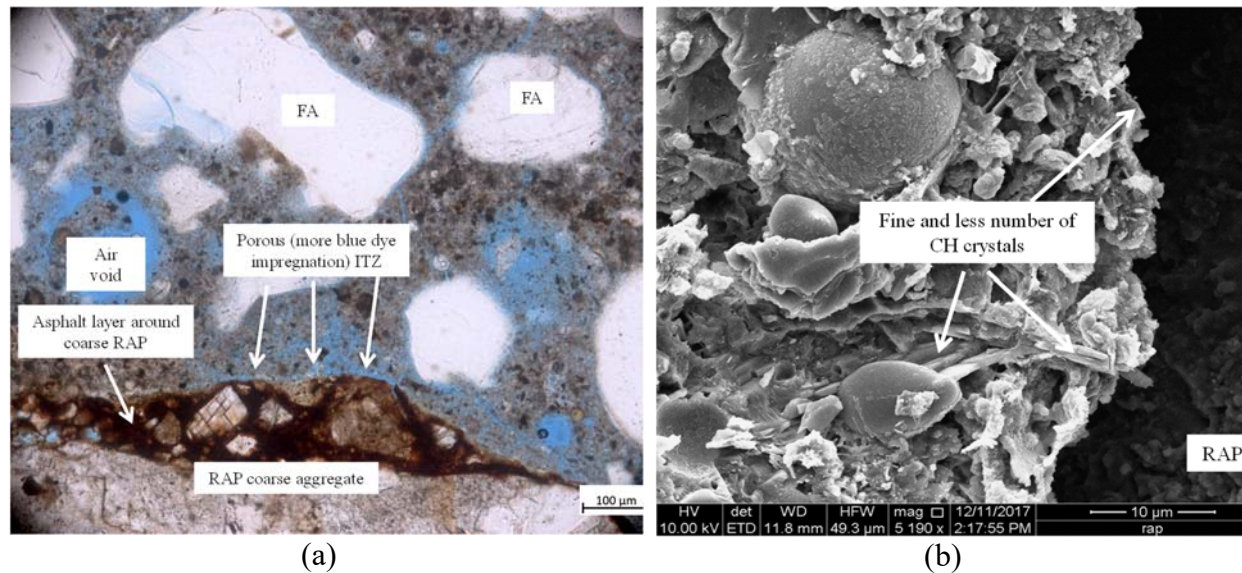


Figure 6 ITZ characteristics (a) porous ITZ around a coarse RAP manifested by high blue dye impregnation, RAP-PCC sample 0.40_520_40HOU, TH, TROM, (b) Porous nature of ITZ with fine and less number of CH crystals around RAP particle in sample 0.40_520_40HOU, SEM image.

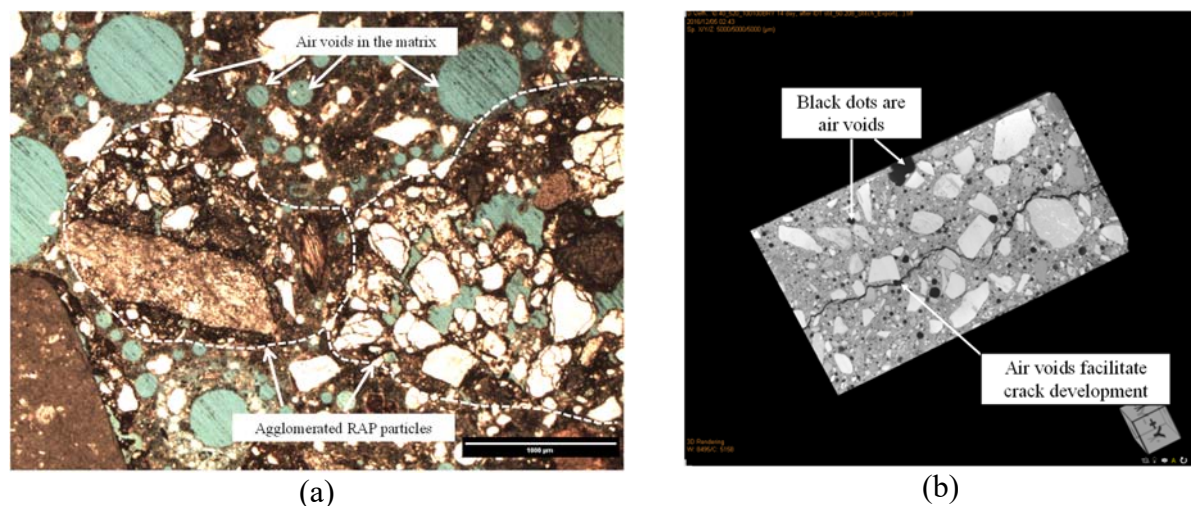


Figure 7 High porosity when high amounts of RAP are added: (a) high air voids in the cement paste mortar around an agglomerated RAP particles, 0.40_520_100BRY/100BRY, TH, TROM, (b) high amounts of pores facilitate crack initiation and propagation (0.40_520_100BRY/100BRY, observed under x-ray microscope).

25-cm 0.40_520_REF	27.5-cm 0.40_520_40BRY	6.25-cm 0.40_580_REF
15-cm cement stabilized base	15-cm cement stabilized base	18.75-cm 0.40_520_40BRY
25-cm non- stabilized base A-2-4	25-cm non- stabilized base A-2-4	15-cm cement stabilized base
Subgrade A-7-5	Subgrade A-7-5	25-cm non- stabilized base A-2-4
Single-lift plain PCC pavement	Single-lift RAP-PCC pavement	Two-lift concrete pavement

Figure 8 Pavement structures evaluated in the EIO-LCA

Investigation of High Strength Concrete Behavior Made with Very High Percentages of Metakaolin and Steel Fibers

Mohammed S. Eisa, Ahmed Ibrahim, and Olaniyi Arowojolu

Synopsis: High strength concrete (HSC) is considered a material which have been implemented in many construction applications. The effect of Metakaolin (MK) and steel fiber (SF) combinations on the mechanical properties of HSC was investigated in this paper. Concrete mixtures' compressive strength split tensile strength and bond strength were evaluated. All mixtures were designed as a grade M60 with various levels of cement replacement with high percentages of MK (10%, 15%, 20%, 30%, 40%, and 50% by weight of cement) and steel fibers (0.25% and 0.50% by volume fraction). The results of this study were compared to the recent similar studies conducted, and it showed consistence conclusions. Test results revealed that a 15% of MK as replacement of cement showed the highest compressive and tensile strengths. Even with 50% of cement replacement with MK and SF, the mixtures showed good mechanical properties compared to the 100% cement concrete.

Keywords: Steel fiber, Metakaolin, Compressive strength, Tensile strength and bond strength

Investigation of High Strength Concrete Behavior Made with Very High Percentages of Metakaolin and Steel Fibers

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INTRODUCTION

The great importance of concrete lies in being the second most consumed material after water, shaping the construction environment all over the world. In several applications, concrete is selected due to its remarkable strength and low maintenance cost. Supplementary cementitious materials (SCMs) such as ground granulated blast furnace slag, fly ash, silica fume or other mineral admixtures have been widely used in concrete production for decades to improve its properties both in the fresh and hardened state. Sabir et al. [1] conducted a study on the utilization of MK as a pozzolanic material for mortar and concrete. They reported that the usage of MK as a pozzolana helped in the development of early age strength and some improvement in the long-term strength.

Recent studies focused on the hydration mechanism of SCMs in the presence of MK and the application of MK as a cement replacement material. The results of those studies showed that the performance of concrete made with MK in corrosive surroundings are optimal [2]. HSC incorporates a higher quantity of binder, lower water content, a higher fine aggregate content, and a lesser amount and nominal size of coarse aggregate than conventional concrete [3]. MK is a SCM that conforms to ASTM C618 [4], with a Class N pozzolan specifications. MK is considered a unique material because it is neither a by-product of an industrial process nor is fully natural; it is obtained from minerals' natural occurrence and is produced particularly for cementing applications [5]. Although MK is quite a new material in the domain of concrete industry, it has a significant effect in enhancing strength, reducing concrete deterioration due to sulphate attacks and in enhancing air-void networks within concrete microstructure. Pozzolanic reactions modify the microstructure of concrete and chemistry of hydration products through the consumption of the emitted calcium hydroxide and creation of additional calcium silicate hydrate (CSH), resulting in an increased strength [6]. MK has been used in cement replacement up to 15% [7], and the study showed that 10% is the optimum level of replacement. Kim et al. [8] investigated the effect of MK on the tensile strength of concrete, where cement was partially replaced in HSC with Korean MK at levels of 0%, 5%, 10%, 15%, and 20%, by weight. Fixed water-to-binder (w/b) ratio of 0.25 and various dosages of superplasticizer (SP) were used. All concrete mixtures contained 141 kg/m³ of fly ash. The results indicated that there was no significant effect of 5%, 10%, and 15% MK on the splitting tensile strength, whilst the inclusion of 20% MK exhibited a slight reduction in the

splitting tensile strength. Multiple mechanical and durability tests on concrete mixtures with various replacement of cement by silica fume and MK were conducted by [9]. The study reported that, appropriate strength was obtained for a substitution rate of MK to binder ranging between 10% and 15%.

Fibers are being added to concrete to improve its mechanical properties such as tensile strength, fracture toughness, and brittleness. In the past, fiber reinforce concrete (FRC) was mainly used for pavements and industrial floors [10]. Nowadays, FRC is being used for a wide range of applications such as: bridges, tunnels and canal linings, hydraulic structures, pipes, explosion-resistant structures, safety vaults, cladding and roller compacted concrete [11].

Ding et al. 2002 [12] investigated the influence of MK and silica fume on the compressive strength of concrete. They reported that both materials were influential in increasing strength beyond 14 days. MK and silica fume performed similarly in increasing concrete strength to almost the same extent over control concrete. Ahmed et al. 2012 [13] investigated the Influence of MK on the performance of mortars and concretes. The experimental results have shown that the level of replacements of 10 and 15% MK increased the compressive strength at both early age and at the long-term when compared to control mixtures. Murali et al. 2012 [14] conducted an experimental study on the use of MK as a SCM in concrete and it was found that the use of MK in concrete efficiently improved the strength characteristics and the optimum level of replacement was reported as 7.5%. The results showed that 7.5% of MK increased the compressive strength of concrete by 14.2%.

Quian et al. 2001 [15] investigated the effect of MK on the tensile strength of HPC. In their study, cement was partially replaced with MK at various levels. The study reported that the tensile strength was increased systematically with increasing MK content. The average tensile strength increased over controls were 7%, 16%, and 28% at MK content of 5%, 10%, and 15%, respectively. Quian et al. [16] investigated the effect of MK on the bond strength of concrete. Cement was partially replaced in concrete with MK at various levels. They reported that MK replacement level of 5% had little effect on bond strength. At 10% and 15% replacement, the 28 days' bond strength increased by 32% and 38%, respectively compared to specimens without MK. Other studies investigated the properties of high strength concrete with the inclusion of MK; Eva Vejmelková et al. (2010) [17], Viswanadha et al. (2014) [20], Abdul Razak et al. (2005) [18]. Most of those studies recommended the use of MK at a low percentage (15%) of cement replacement. Burciaga-Díaz et al. (2017) [19] conducted experiments utilizing cement pastes made of slag and MK, cured under various conditions. It was concluded that samples of 100% slag developed the highest strength of 120 MPa with 5% Na₂O; and a 100% MK required 15% Na₂O to develop high strength. Another study reported the optimal dosage of MK usage in high performance concrete, Michal et al. (2016) [20]. MK was added to the mixtures of high-performance concrete in the range of 0 to 25% of cement weight. The study reported that the inclusion of MK in high performance concrete affects positively the compressive strength and rheological behavior and recommended higher doses of MK which is in agreement with the results of previous studies [21]. While improvements in concrete compressive strengths have been achieved using MK as a replacement for cement, it is also necessary to correspondingly increase its tensile strength, where such increase will improve its usability in structural applications.

Therefore, this paper aims to study the mechanical properties of HSC made by replacement of cement with MK up to 50% in the presence of steel fibers (SF), with focus on fresh and mechanical properties (compressive, tensile, and bond). The outcome of the study will add to existing knowledge on the behavior of HSC made with very high percentages of MK and steel fibers.

RESEARCH SIGNIFICANCE

The significance of this work is derived from the need of looking deeply for various alternatives of new materials for cement replacement. Waste by products such as fly ash, slag and silica fumes are very common cement replacement materials in concrete industry and have been used for decades. This work proposes the implementation of MK as cement replacement material with various percentages in addition to steel fibers to enhance the durability and ductility of high strength concrete. The study wide range data of compressive, tensile strength and bond strength.

EXPERIMENTAL PROGRAM

A total of 21 mixtures with standard test specimens (cubes and cylinders) were divided into three groups. The first group had 0% volume fraction of SF and various levels of cement replacement with MK (10%, 15%, 20%, 30%, 40%, and 50%). The second and third groups were similar to the first group except that the fiber content was varied as 0.25% and 0.50% as volume fractions for groups 2 and 3, respectively.

Locally produced Ordinary Portland Cement (OPC) with grade 52.5N conforming to ASTM C150 of low alkali Portland cement was used in this study. The M60 concrete has a Characteristic Compressive Strength at 28 days = 60 N/mm². Clean natural sand was used and it was free from impurities, such as silt and clay. Clean natural well-graded coarse aggregates with nominal maximum size of 10 mm, conforming to grading III as per ASTM C33 was used in the mix proportioning. MK was produced by heat-treating kaolin (up to 800°C), as one of the most abundant natural minerals. Kaolin is a fine, white clay that has traditionally been used in the manufacturing of porcelain and as a coating for papers. MK was brought from Sindhu Chemical Products SCP, India. Table 1 gives the physical and chemical properties of MK according to the manufacturer information. Hooked ended SF obtained from Sika chemicals was selected for use in this study. The aspect ratio of the fibers was 30 with a length of 30 mm and a diameter of 1 mm. The properties of steel fibers, according to the manufacture information are given in Table 2. A high range water reducer (HRWR) was used to attain sufficient workability during mixing and casting. The admixture conforms to ASTM C494. The HRWR was brought from Sika chemicals with the commercial name of “Sikament R2004”. Potable water free from impurities was used in concrete mixing. The physical properties of aggregates and the mechanical properties of cement are shown in Tables 3 and 4.

Mix Proportions and Test Specimens

In this study, all the mixes and testing were done according to ASTM guidelines. The batched concrete ingredients were mixed according to ASTM C192. ASTM standards C39, C496, and D4796 were used to perform the compressive tensile strength and bond strength tests. The control mixtures were designed to achieve a target compressive strength of 60 MPa (M60), with proportions shown in **Table 5**. Standard cubes of size 100 mm x 100 mm x 100 mm, cylinders with 100 mm diameter x 200 mm height were prepared using the standard molds. The specimens were named using notations which refer to the percentage of MK replacement and fibers content

in each mix. For example, “MK0” refers to a 0.0% of MK replacement, and “MK10” refers to 10% MK replacement.

RESULTS AND DISCUSSION

This section presents the test results of the compressive, tensile and bond strengths of the proposed concrete mixtures. The results are based on the average of three standard-cured specimens made from the same concrete batch and tested at the same time. The tests were carried out for both control and developed concrete mixes at the desired test age.

Compressive strength

The test results of cube compressive strength at 3, 7- and 28-days’ age are presented in Fig. 1(a). The variation in compressive strength for specimens containing MK and varied volume fraction of SF at 3, 7 and 28 days are shown in Fig. 1(b and c). Discussions of the test results at different ages are addressed in the below sections.

As shown in Fig. 1, all the concrete specimens achieved and exceeded the target compressive strength of 60 MPa at 28-days for all levels of MK replacements. The compressive strength of specimens at 28-days increased as the MK content increased up-to MK replacement of 15%, and after that the compressive strength slightly decreased. The tested specimens showed an average compressive strength of 27.65, 29.30, and 33.43 MPa at the age of 3 days for 0%, 0.25% and 0.50% steel fibers respectively. A negligible increase in the compressive strength of all mixtures with various MK percentages at 3-days was observed. At age of 7-days, the highest increase in compressive strength was found to occur when cement was replaced by 15% of MK. While at a higher cement replacement by 50% MK, the compressive strength decreased by 9% when compared to the mixture with no MK. The highest compressive strength obtained at 28-days was 74.48 MPa at MK content of 15% and the lowest was 59.89 MPa with MK content of 50%. It is clear that the replacement of cement by 50% is very feasible as the concrete mixtures for group 1 showed very comparable 28th day compressive strength to the control mixture (with no MK). The reduction in compressive strength for MK 20, 30, 40, and 50 compared to MK15 is because of clinker dilution effect (high cement replacement level will inhibit rate of strength gain). Parande et al. (2008) [22] and Ding et al. (1999) [23] reported that the chemical reaction of MK with Ca(OH)_2 has a negative effect on pozzolanic reactions, which justifies the reduction in compressive strengths at a higher cement replacement by MK.

When steel fibers were added to the mixtures, a different behavior was observed as shown in Fig. 1(b and c). At age of 3 days, a 50% MK content has a negligible effect on the compressive strength for both SF volume fractions as shown in Fig. 1(a and b). The compressive strengths at 7 and 28 days increased by 8% and 12% at a replacement level of 15% MK and 0.25% fiber content, whereas it increased by 8% and 19% at 7 and 28 days at a replacement level of 15% MK with a SF fraction of 0.50%. The rate of strength gain decreased when the increase in the MK content beyond the 20% level of replacement. Overall, the addition of steel fibers with the MK replacement level produced compressive strengths of 77.87 MPa and 87.54 MPa with SF fractions of 0.25% and 0.50%, respectively. Fig. 2 shows a typical compression failure of cubical specimen.

The relationship between compressive strength of mixtures made without fibers and with fibers for the same MK replacement levels is shown in Fig. 3. It is observed that the strength of a mixture with SF is almost a linear function of the strength of the control mixture (G1). Subsequently, the

best-fit linear equation for each case was determined using simple regression analysis based on least squares method. The coefficient of determination (R^2) for each linear equation was found to be very close to unity, indicating that the linear model is a good description for the relationship between the two variables. The lowest R^2 value obtained from the regression analysis was 0.97 for G2 and 0.92 for G2. A correlation between the compressive strength and the tensile strength was developed as follow:

$$f_t = 0.149 (f'_c)^{0.8316} \quad (1)$$

f_t : tensile strength of Concrete
 f'_c : Concrete strength of Concrete

Split tensile strength

Tensile strength is one of the basic and important mechanical properties of concrete. The test results of the standard cylinder split tensile strength at 28 days for all mixtures are presented in Fig. 4. Mixtures in group G1 with 0.0% SF showed negligible increase in tensile strength when MK content is increased up to 15%, and after that an insignificant decrease was observed. In G2, the highest tensile strength was observed as 5.95 MPa for mix MK15 against 5.48 MPa obtained in G1. In group G2, a slight decrease in the tensile strength for MK content of 50% was observed as shown in Fig. 3. Mixture MK15 (G 2) showed 8.0 % increase in tensile strength compared to mix MK15 of G1. The final group G3, showed very slight increase in tensile strength compared to group G1, with highest increase in split tensile strength of 13% at MK content of 15%. It is concluded that steel fibers enhanced the tensile strength as expected but in overall, mixtures showed very comparable tensile strength when cement was replaced with very high percentage of MK. Increasing the MK content beyond the 15% for all mixtures with a 0.25% volume fraction of steel fibers, insignificantly decreased the tensile strength as shown in Fig. 4.

Table 6 shows the ratio of the tensile strength to cube compressive strength of all mixtures at 28 days. These ratios are lower than the range (of about 9–10 %) for medium strength concrete reported earlier [24, 25]. This observation was shown in all mixtures regardless the MK replacement ratio or the existence of steel fibers. This indicates that as the compressive strength increases, the ratio of tensile-to-compressive strength decrease which is consistent with the results reported by other investigators [25].

Bond strength

Bond between steel reinforcement and concrete is essential to ensure the composite interaction of the two materials under various load applications and to achieve certain serviceability requirements. There are many factors influencing the bond strength between concrete and steel, such as concrete strength, concrete composition and environments. In this study, 10 mm steel bars were embedded in the center of 100 mm x 200 mm cylinders with a bond length of 100 mm. The test results of cylinder bond strength at 28 days' age are presented in Fig. 5. For group G1, the highest bond strength was observed as 11.15 MPa, for mixture MK15, and it decreased to 7.8 MPa for MK50 with a 30% reduction in the bond strength. For G2, the MK15 again achieved the highest bond strength of 11.78 MPa. Adding 0.25% steel fibers enhanced the bond strength for MK15 in groups G2, and G3 by 5.6%, and 7.0%, respectively compared to G1. Fig. 6 shows a typical failure of a specimen under the pullout test. Overall, increasing the content of MK beyond 15%, led to a decrease in the bond strength for all the mixtures. Fig. 7 shows the correlations between the

compressive strength of all mixtures, the tensile and bond strength. The R^2 value for the compressive-tensile strength was 0.77 which could be considered reasonable with the targeted high percentage of cement replacement, whereas the R^2 of the compressive-bond strength has a very low value which indicates bad correlation index, and which agrees with the results shown in Fig 7.

Table 7 shows a comparison of the results of this study with results available in the literature obtained from other authors. Most of the studies recommended that optimum MK replacement is 15%, which was based on mechanical and durability properties. In this study, the authors extended the replacement levels up to 50% for the HSC mixtures, where it showed outer performance in terms of mechanical properties such compressive strength, tensile and bond strength.

CONCLUSIONS AND RECOMMENDATIONS

This study presented the results of 21 high strength concrete mixtures prepared and tested to investigate the mechanical properties of high strength concrete made with high percentages of combinations of MK and steel fibers. The MK was used as a partial replacement for cement. The level of replacement varied between 0.0% and 50%, coupled with addition of steel fibers in a volume fraction of 0.25% and 0.50%. The highest compressive strength was obtained at a cement replacement level of 15% either in mixtures made without or with steel fibers. The relationship between the compressive strength of mixtures made with and without steel fibers with same level of MK replacements was linear with very good correlation factors. All concrete mixtures showed high compressive strength equal or exceeded the design compressive strength of 60 MPa, even with the 50% cement replacement with MK and steel fibers. The addition of steel fibers enhanced the tensile strength at 28-days with highest gain obtained at a 15% MK replacement level. The improvement levels were 9%, 11.2%, and 11% for the mixtures without fibers, with 0.25% fiber and 0.50% fibers, respectively. It was observed that all mixtures displayed higher bond strength at a replacement level of 15% and a decrease of about 25% was observed for mixtures having MK of 20% to 50%. It is believed that the developed mixtures when put into application would significantly decrease the CO₂ emissions, even at a cement replacement up to 50%. While the mechanical properties have been successfully measured in this work, the authors believed that more research is needed to study the hydration of concrete mixtures containing MK using microscopy analysis.

REFERENCES

- [1] Sabir, B., Wild, S., and Bai, J. Metakaolin and calcined clays as pozzolans for concrete: a review. *Cement and Concrete Composites*, 2001, vol. 23(6), pp.441-454.
- [2] Mlinárik, L., and Kopecký, K. Impact of Metakaolin - a new supplementary material - on the hydration mechanism of cements, *Acta Technica Napocensis: Civil Engineering & Architecture*. 2013. vol. 56 (2), pp. 100 – 110.
- [3] ASTM C618-15, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete, ASTM International, West Conshohocken, PA, 2015, www.astm.org
- [4] Brooks, G., and Johhari, M. Use of steel fiber reinforced concrete in bridge decks and pavements *Steel Fiber Concrete*. Elsevier Applied Sciences Publishers Ltd, 1986, pp.67-108.
- [5] Sanjay, N., Anil, K., and Subhash, S. Metakaolin - Pozzolanic Material for Cement in High Strength Concrete, *IOSR Journal of Mechanical and Civil Engineering IOSR-JMCE*. 2013, pp.46-49
- [6] Dinakar, P., Sahoo, P.K. & Sriram, G. Effect of Metakaolin Content on the Properties of High Strength Concrete. *Int J Concr Struct Mater*, 2013, vol. 7: 215-220.
- [7] Kim, H., Lee, S., and Moon, H., Strength Properties and Durability Aspects of High Strength Concrete using Korean Metakaolin. *Construction and Building Materials*, 2007, vol. 21, pp. 1229-1235.
- [8] Siddique, R., and Kahn, M. *Supplementary Cementing Materials. A comprehensive review of Supplementary Cementing Materials*. Springer-Verlag Berlin Heidelberg, 2011, pp. 175-230.
- [9] Brooks, J., and Johari, M. 2001. Effect of Metakaolin on creep and shrinkage of concrete. *Cement and Concrete Composites*, vol. 23(6), pp.495-502.
- [10] Balaguru, P., and Shah, S. *Fiber reinforced cement composites*. McGraw International Edition: New York, 1992.
- [11] Ding, J. and Li, Z. Effects of Metakaolin and silica fume on properties of concrete. *ACI Materials Journal*, 2002, vol. 99(4), pp. 393-398.
- [12] Ahmed, M., Belakrouf, A., and Kenai, S. Influence of Metakaolin on the Performance of Mortars and Concretes. *World Academy of Science, Engineering and Technology International. Journal of Civil, Environmental, Structural, Construction and Architectural Engineering*, 2012, vol. 6(11), pp. 1010-1013.
- [13] Murali, G., and Sruthee, P. Experimental study of concrete with Metakaolin as partial replacement of cement. *International journal emerging trends in engineering and development*, 2012, vol. 2(4), pp.344-348.
- [14] Quian, X. and Li, Z. The relationships between stress and strain for high performance concrete with Metakaolin. *Cement and Concrete Research*, 2001, vol. 31(11), pp.1607-1611.

- [15] Tanyıldızı, H., Yazıcıoğlu, S. Effect of mineral admixtures on bond strength of concrete and reinforcement. *Firat University J Sci*, 2006, vol.18, pp. 351-357.
- [16] Yeih, W., Huang, R., Chang, J., and Yang, C. A pullout test for determining interface properties between rebar and concrete. *Advanced Cement Based Materials*, 1997, vol. 5, pp. 57-65.
- [17] Vejmelková, Eva., Pavlíková, Milena, Keppert, Martin, Keršner, Zbyňk, Rovnaníková, Pavla, Ondráček, Michal, Sedlmajer, Martin, and Cerny Roberst. High performance concrete with Czech metakaolin: Experimental analysis of strength, toughness and durability characteristics, *Construction and Building Materials*, 2010, vol. 24, pp.1404–1411.
- [18] D.Viswanadha Varma, G.V. Rama Rao. Influence of Metakaolin in High Strength Concrete of M70 Grade for Various Temperatures and Acidic Medium. *IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)*. 2014, vol.11, Issue 3 Ver. VII, pp. 32-37
- [19] Abdul Razak, H., Wong, H.S. Strength estimation model for high-strength concrete incorporating metakaolin and silica fume. *Cement and Concrete Research*, 2005, vol. 35, pp. 688– 695
- [20] O. Burciaga-Díaz, R.X. Magallanes-Rivera & J.I. Escalante-García. 2013, Vol. 2, Iss. 2, *Journal of Sustainable Cement-Based Materials*.
- [21] Michal, Z., Tomáš, V., and Lenka, L. Dosage of Metakaolin in High Performance Concrete
Key Engineering Materials, 2016.
- [22] Parande, A. K., Ramesh Babu, B., Karthik, M. A., Kumar, K. K., & Palaniswamy, N. Study on strength and corrosion performance for steel embedded in metakaolin blended concrete/mortar. *Construction and Building Materials*, 2008, 22(3), 127–134.
- [23] Ding, Z., Zhang, D., & Yu, R. High strength composite cement. *China Building & Material Science Technology*, 1999, 1, 14–17.
- [24] Neville, A. M. Concrete with particular properties. In *Properties of concrete*, Harlow, UK: Longman. 1997, 653–672).
- [25] Haque, M. N., & Kayali, O. Properties of high strength concrete using a fine fly ash. *Cement and Concrete Research*, 1998, 28(10), 1445–1452.
- [26] Saridemir, M., Secercan, M.H. and Çelikten, S. “Mechanical properties of SFRHSC with metakaolin and ground pumice: Experimental and predictive study”, *Steel Compos. Struct.*, 2017, 23(5), 543-555.

Table 1-Physical and chemical properties of Metakaolin

Chemical Composition	Silica (SiO ₂)	Alumina (Al ₂ O ₃)	Ferric oxide (Fe ₂ O ₃)	Calcium oxide (CaO)	Magnesium oxide (MgO)	Titanium dioxide (TiO ₂)
(%) By weight	53.26	43.93	0.3	0.36	0.49	1.25
Specific gravity (g/cm ³)	Physical form	Color				
2.50	Powder	Off-white				

Table 2-Typical steel fiber properties

Property	Fiber type	Fiber diameter (D)	Fiber length (L)	Aspect ratio (L/D)	Tensile strength
Description	Hooked end steel fiber	1 mm	30 mm	30 mm	900 MPa

Table 3-Physical properties of aggregates

Aggregate type	Specific gravity	Volumetric weight (t/m ³)	% Voids
Sand	2.65	1.73	34.3
Gravel	2.67	1.69	36.7

Table 4-Chemical properties of cement

Physical property	Tested Value	Standard limits
Consistency of standard cement paste	Water content as % by weight of cement = 28%	26% - 30%
Setting time	Initial= 1 hrs., 57 min. Final = 4 hrs., 13 min.	Min. 45 minutes Max. 10 hrs.
Compressive strength	3 days= 235 kg/cm ² 7 days= 335 kg/cm ²	Min. 180 kg/cm ² Min. 270 kg/cm ²
Fineness of cement	3400 cm ² /gm	Min. 2750 cm ² /gm