EFFECT OF CEMENT KILN DUST ON SOME MECHANICAL PROPERTIES OF CONCRETE

A Thesis

Submitted to the College of Engineering of the University of Babylon in Partial Fulfillment of the Requirements for the Degree of Master of Science in Civil Engineering

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October ٢٠٠٢ **Shaaban ١٤٢٣**

تأثير غبار افران السمنت على بعض الخواص الميكانيكية للخرسانة

رسالة

مقدمة إلى كلية الهندسة في جامعة بابل

كجزء من متطلبات نيل درجة الماجستير

في علوم الهندسة المدنية

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هُوَ الَّذِي بَعَثَ فِي الْأُمِّيِّينَ رَسُولًا مِنْهُمْ يَتْلُو عَلَيْهِمْ آيَاتِهِ وَيُزَكِّيهِمْ وَيُعَلِّمُهُمُ الْكِتَابَ وَالْحِكْمَةَ وَإِنْ كَانُوا مِنْ قَبْلُ لَفِي ضَلَالٍ مُبِينٍ

صدق الله العظيم

سورة الجمعة ، الاية ٢

الخلاصة

أن المشاكل التقنية والاقتصادية الناشئة من نقل مادة غبار أفران السمنت من المعمل إلى الخارج ,إضافة إلى ضررها الكبير على البيئة المجاورة ، يبرر ضرورة إجراء البحث على تلك المادة. لذا تهدف هذه الدراسة إلى تحري إمكانية استخدام غبار السمنت في أعمال الخرسانة والمونة كبديل جزئي عن السمنت أو الرمل.

ينقسم الجانب العملي في هذا البحث إلى جزئين ، الجزء الأول يركز على دراسة تأثيرات إجراء تعويض جزئي عن السمنت بنسب وزنية مماثلة من الغبار. أما الجزء الثاني فيتضمن استخدام الغبار كبديل جزئي عن الرمل. حيث أجريت الدراسة على خلطات من المونة والخرسانة وقد وصلت النسب المستخدمة من الغبار إلى ٤٠% و٥٠% في المونة والخرسانة على التوالي.

أظهرت النتائج أن زيادة نسب إحلال الغبار كتعويض جزئي عن السمنت يؤدي إلى انخفاض في مقاومة الأنضغاط،حيث بلغت مقاومة الخرسانة والمونة حوالي٩١% و ٩٥% على التوالي من مقاومة الخلطات المرجعية عند نسبة إحلال ١٠% من الغبار. من ناحية أخرى، فقد كان لاستخدام غبار السمنت كبديل جزئي عن الرمل تاثير ملحوظ على زيادة مقاومة الأنضغاط للخلطات الضعيفة نسبياً ، خصوصاً عند الأعمار المبكرة ، بينما يكون له تأثير معاكس على مقاومة الأنضغاط للخلطات الغنية. إن إضافة ٢٠% من الغبار كبديل جزئي عن الرمل في الخلطات الضعيفة يؤدي إلى تحسن مقاومة الأنضغاط بنسب تتراوح بين ٢٥.٥% و ١٦% في الخرسانة والمونة على التوالي.

أما الخواص الأخرى للخرسانة والتي تتضمن معاير التصدع ، مقاومة الشد الانشطاري، الكثافة وسرعة الموجات فوق الصوتية ، فقد أبدت سلوكاً مشابهاً لمقاومة ألانضغاط. كما أظهرت النتائج أيضاً أن غبار السمنت يؤدي إلى زيادة في انكماش الجفاف والتمدد لنماذج المونة، ولكن تلك الزيادة لم تكن بشكل ملحوظ عند إحلال ١٠%من الغبار كبديل عن السمنت أو الرمل.

مما سبق ووفقاً لنتائج هذه الدراسة يمكن الاستنتاج بأن غبار أفران السمنت يمكن أن يستخدم في الأعمال الإنشائية على أن لا تزيد نسب الاستبدال عن ١٠% من السمنت و٢٠% من الرمل دون حصول تأثير سلبي واضح على أداء الخرسانة والمونة.

ACKNOWLEDGMENTS

I wish to express my deep appreciation to my supervisors ***Dr. Maher B. Al-Samaani*** and ***Dr. Mahdi S. Essa*** for suggesting the problem, their valuable assistance and continuous guidance.

I am grateful to the Dean of the College of Engineering and the Head of the Civil Engineering Department in the University of Babylon for their co-operation and assistance.

I would like to thank the General Company of Hitteen , with whom the research work contract was made.

I also a knowledge the assistance received from the staff of Babylon Construction Laboratory of NCCL especially from Mr. Amer Abdul-Hamza, Mr. Zuhair Hassan and Mr. Haider Owaid.

Special thanks are presented to Mr. Marza Karim and Mr. Ali Hassoon for their help during the research.

Finally, gratitude go to my family for their encouragement and support during the course of this work.

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ABSTRACT

The technical and economical problems that arise from transportation of cement kiln dust (CKD) outside the cement plant, as well as the severe pollution of the surrounding environment by this dust, makes the subject matter worth studies. This study was thus conducted to examine the feasibility of using CKD in concrete and mortar mixes as partial replacement for cement or sand.

The experimental program is divided into two parts. The first part consists of studying the effects of a partial replacement of cement by an equal weight of CKD. In the second part, CKD was used as a partial weight replacement of sand. The study was conducted on mixes of mortar and concrete. The percentages of CKD replacement used were up to ٤٠ and ٥٠ percent in mortar and concrete respectively.

The results indicate that increasing the percentages of cement partial replacement by CKD leads to decrease the compressive strength of concrete and mortar. Up to ١٠٪ of cement replacement by CKD, the strength of concrete and mortar reachs about ٩١ and ٩٥ percent of the control strengths respectively. On the other hand, the presence of CKD as sand partial replacement increases the compressive strength of relatively lean mixes, especially at early ages, while adversely affects the strength of rich mixes. The inclusion of ٢٠٪ of CKD by weight of sand in lean mixes, results in an improvement in compressive strength by about ٢٥.٥ and ١٦ percent in concrete and mortar respectively.

Other concrete properties including modulus of rupture, splitting tensile strength, density and ultrasonic pulse velocity, show trends similar to that observed in compressive strength. The analysis of the test results also shows that the drying shrinkage and expansion of mortar specimens increase when CKD content increases. However, these volume changes are slightly affected when up to ١٠٪ of CKD is used as cement or sand replacement.

Finally, the results suggest that CKD could be used in construction industries by up to ١٠٪ as cement replacement and ٢٠٪ as sand replacement without detrimental effects on the performance of concrete and mortar.

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LIST OF NOTATIONS

SYMBOL	DESCRIPTION
W/C	Water to cement ratio.
W/b	Water to binder ratio.
L.O.I.	Loss on ignition.
I.R.	Insoluble residue.
V	Ultrasonic pulse velocity.
T	Transit time.
F_{cu}	Concrete compressive strength.
ρ	Concrete density.
CRA	Cement replacement (١:٢:٤ concrete mix).
CRB	Cement replacement (١:١.٥:٣ concrete mix).
SRA	Sand replacement (١:٢:٤ concrete mix).
SRB	Sand replacement (١:١.٥:٣ concrete mix).
CRL	Cement replacement (١:٣ mortar mix).
CRM	Cement replacement (١:٢ mortar mix).
SRL	Sand replacement (١:٣ mortar mix).
SRM	Sand replacement (١:٢ mortar mix).

Note*: Other symbols are defined as they appear in the text.*

CERTIFICATION

We certify that we have read this thesis, titled (**Effect of Cement Kiln Dust on Some Mechanical Properties of Concrete**), and as examining committee examined the student **Mohammed Shamel Mohammed Al-Husseini** in its contents and in what is connected with it, and that in our opinion it meets the standard of thesis for the Degree of Master of Science in Civil Engineering (Construction Materials).

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CHAPTER 1

INTRODUCTION

١.١ General

In recent years, considerable researches have been focused on solving environmental problems by the reduction of industrial wastes. Studies have been carried out to investigate the possibilities of using industrial wastes such as fly ash, blast furnace slag, silica fume, cement kiln dust and other wastes as a material replacement in the construction industry.

The use of waste and by-product materials in the construction industry may help to conserve resources of the natural raw materials that are used in the industry, and at the same time, can help to preserve the environment by reducing the disposal of some waste materials [١, ٢, ٣]. These wastes have been mainly used for some time as filler in roads and embankments, but the energy-saving aspect of the utilization of industrial wastes as a concrete ingredient is of special significance. Therefore, many wastes and by-products were found to have potential use in concrete industry [١, ٤, ٥].

It is known that the cement and aggregate are the most important materials in concrete, especially cement, which is expensive and its manufacture involves intensive use of raw materials and energy. Thus, replacement of cement by less expensive materials partially or in full would reduce the cost of construction and simultaneously conserve energy and resource. On the other hand, replacement of fine aggregate by these products will help to treat the wastes disposal problems and conserve the fine aggregate [٦].

Replacement is especially effective when the material substituting happens to be waste material or by-product of another industry. For some of these materials, standard specifications have been developed, while others have no specifications yet. However, typical waste materials that have the best potential are fly ash and blast furnace slag.

1.2 Cement Kiln Dust (CKD)

Cement kiln dust (CKD) is a fine powdery waste generated during the manufacture of Portland cement. As the raw materials for making cement are heated and tumbled in a kiln, dust particles are created and carried with hot exit gases.

To control the dust from escaping into the environment, most of cement plant equipments are working to collect large volumes of dust from the exit gases before they are discharged to the atmosphere [٧]. This dust is collected by using mechanical collectors or electrostatic precipitators.

The percentage of CKD wasted in a cement manufacturing process is (١٥-٢٠) percent of the output of the kiln [١,٢]. Since the chemical components of CKD are nearly the same as the cement raw materials, some of CKD can be recycled into the kiln [٤٤]; however, large quantities of CKD are disposed. Fig.(١-١) demonstrates the pathway taken by materials through a typical cement manufacturing process [٤٥].

There is a great deal of variation between different sources of CKD. The major variables affecting CKD quality are the composition and proportions of the feed materials, type of the kiln, fuel, processing efficiency and the type of the dust collection system [٤٦].

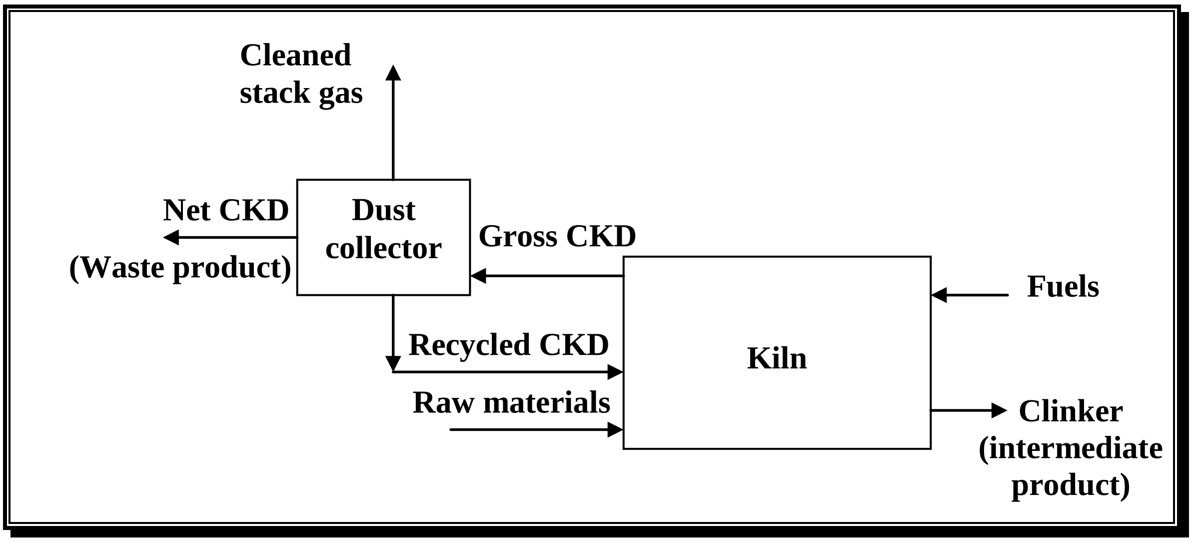

Fig.(1-1): Typical material behavior in a cement kiln system [45].

١.٣ Aim of the Study

Each year, thousands of tons of CKD are disposed by cement industry. Since this material possesses health hazard, storage and transportation problems, and a potential pollution source, therefore, consuming such material in civil engineering works would help to solve some of these problems, and at the same time, could reduce the cost of construction by the conservation energy and resource. However, the aim of the present work is to study the properties of some concrete and mortar mixes when up to ٥٠ percent by weight of ordinary Portland cement as well as fine aggregate are replaced by CKD, and also, to determine the optimum percentages of CKD which could be used in both cement and sand replacement.

١.٤ Research Layout

The work presented in this thesis is given through five chapters. Chapter One represents this introduction. Chapter Two is a review of the previous works on the use of mineral admixtures in concrete; the properties and uses of CKD are also included in this chapter. Chapter Three includes the experimental program, mix proportioning and testing procedures. The results of the experimental tests are presented and discussed in Chapter Four. Chapter Five consists of the conclusions which can be drawn from the results of this research and suggestions for future studies.

CHAPTER 2

REVIEW OF LITERATURE

2.1 Introduction

Portland cement concrete will continue to be the dominating construction material in the future. As with other industries, progress in concrete technology should necessarily take into account the widespread need for conserving resources and environment and gains proper utilization of energy. It can be expected that there will be a major emphasis on the use of wastes and by-products in cement and concrete technology [٨]. As a result, there have been numerous studies on the use of industrial by-products in concrete construction. But the effective use of these materials requires adequate knowledge of their properties and the technical problems associated with their usage [١, ٣].

The ACI Committee ٢١٢ report on admixtures for concrete [٩] classifies both natural minerals and industrial by-products under the term “miniral admixtures” into four types: (١) those that are cementitious, (٢) those that are pozzolanic, (٣) those that are both cementitious and pozzolanic, and (٤) inert or filler materials. However, the extended uses of these materials in the manufacture of concrete are: (a) partial replacement of Portland cement and (b) partial replacement of fine aggregate [٦, ٨, ١٠, ١١, ١٢].

2.2 Mineral Admixtures as Partial Cement Replacement

The use of mineral admixtures such as fly ashes, blast furnace slags and inert or filler materials as a cement replacement is discussed by several authors. **Montgomery *et al*.** [١٣] and **Gopalan** [١٤] reported that the strength contribution of fly ash is due to providing nucleation sites for the growth of hydration products. **Poon *et al*.** [١٥] indicated that fly ash improves the particle packing of the cementitious matrix and contributes to the strength development even when it is not active as a pozzolanic material but acting as a filler. However, **Wong *et al*.** [١٦] observed that the main contribution of fly ash to concrete strength is due to the improvement of the bonding between the cement paste and the aggregate, rather than the enhancement of the strength of cementitious matrix.

As observed by some researchers [١٧, ١٨], fly ash concretes may have better strength performance when they are replaced at lower water to binder (w/b) ratios. It can be concluded that the advances of concrete admixtures technology allow concrete mixtures to be prepared with lower w/b ratios. It is therefore believed that high strength concrete can be obtained with large volumes addition of fly ash. However, the optimum cement replacement to satisfy the strength and durability requirements of fly ash concretes is about ٣٠ percent by weight of cement [١٩, ٢٠, ٢١].

The experimental results were usually obtained from specimens cured in water or moist environments. It should be noticed that fly ash concrete must have adequate curing to enhance performance. **Butler** and **Ashby** [٢٢] and **Haque *et al*.** [٢٣] have reported that structural grade concretes containing fly ash must be adequately cured. **Poon *et al*.** [١٥] observed that the fly ash concrete is more sensitive to the curing condition and requires a longer curing time because its hydration rate is slower than that of plain concrete. Also, the benefits of using fly ash in concretes may be diminished due to inadequate curing.

Many studies were carried out to investigate the effect of blast furnace slag on the properties of concrete. This material is widely being used as a cementitious ingredient of concrete and a valuable cement replacement material that imparts some specific qualities to the concrete [٢٤]. If a part of the Portland cement of concrete is substituted by slag, the strength gain is changed so that early strength decreases and later strength is either the same as, or higher than that of Portland cement concrete [٤,٢٥]. Such concretes have excellent durability characteristics than concretes made with normal Portland cement only [٢٦, ٢٧, ٢٨].

It could be noticed that concrete with compressive strength exceeding ٥٠ MPa and of good durability, could be produced with high levels (٦٥-٧٥) percent of slag replacement [٢٤, ٢٦, ٢٩]. But the disadvantage of the high levels slag concrete seems to be the low strength at early ages. Also, the results show that even ٧ days wet curing was inadequate for high levels of slag replacement, and that continued exposure to a drying environment has adverse effects on the long term durability [٢٤, ٢٩].

According to the results of some studies on the effect of inert or filler materials on the properties of concrete, **Soroka** and **Stern** [٣٠] concluded that fillers affect strength through their accelerating the cement hydration. Another investigation carried out by **Soroka** and **Setter** [٣١] stated that fillers effect on strength is primarily accelerating on the cement hydration. This improvement in strength can also be attributed to the increase in the density of the concrete due to increasing filler content in the mix.

Jackson and **Dhir** [٣٢] reported that the inert materials may result in some reduction in concrete strength, althouth they improve workability, stability and impermeability of concrete. **Chan** and **Wu** [٣٣] stated that the durable concrete could be made with ٢٥ percent of cement replaced with inert materials such as silts and clays. Up to this level, the compressive strength was slightly lower than that of the control mix. They also indicated that the inert materials could give more micro-filler effect and nucleation sites for cement hydration.

2.3 Mineral Admixtures as Fine Aggregate

Many researchers have tried to investigate the mechanical properties of concrete incorporating percentages of mineral admixtures as fine aggregate. Generally, this concrete exhibits compressive strength equal to or above the strength exhibited by ordinary concrete [١٢].

Malhotra and **Carette** [٦] studied the properties of concrete incorporating various percentages of limestone dust as a partial replacement for fine aggregate. The results showed that there is a significant increase in strength with increasing the amount of limestone dust in lean concrete mixes. However, this is not evident in concrete mixes which are relatively rich in cement.

Maslehuddin *et al.* [١٢] investigated the characteristics of concrete mixtures in which fly ash was used as a partial replacement for fine aggregate. The results show that the addition of fly ash improves the early age compressive strength and long term properties of concrete. The superior performance of these mixtures compared to plain concrete mixtures is attributable to the densification of the concrete structures.

Lewist [٣٤] reported that the partial substitution of fine aggregate by slag in structural grade concretes resulted in significant increase in strength for a given cement content. This increase in strength was more pronounced in lean mixes. **Abbas** [٣٥] stated that up to ٣٠ percent of fine aggregate replaced by slag in concrete demonstrates acceptable levels of performance in the workability, durability and compressive strength.

Ezeldin *et al*. [٣٦] studied the effect of two different soil types ,well graded sand and silty sand, as partial fine aggregate replacement in concrete. The results indicated that when using well graded sand, the initial and final setting times were increased by about ٤٠ percent, but the compressive strength of concrete was slightly lower than that of the control concrete. However, when silty sand was used, less favorable results were obtained.

Falade [٣٧] investigated the effect of laterite fine aggregate instead of sand on the workability and compressive strength of concrete. He used different water-cement ratios and mix proportions. The results showed that the water requirement for a mix increased with the increase in laterite / cement ratio. Also, the compressive strength decreased with the increase in laterite/cement ratio. The decrease in strength may be attributed to the increase in the quantity of mixing water.

Haque [٣٨] has studied the effects of fine sand and differing quantities of kaolinitic clay on the strength of concrete. It was concluded that the use of fine sand caused a reduction in concrete strength. However, the loss in strength due to the addition of kaolinitic clay up to ١٠٪ of the total weight of aggregate seemed to be a function of the increase in the surface area of the aggregate and a consequent increase in the water-cement ratio.

According to **Neville** [٣٩], silt and fine dust should not be present in excessive quantities because, owing to their fineness and therefore large surface area, silt and fine dust increase the amount of water necessary to wet all the particles in the mix. **Teychenne** [٤٠] has reported that increasing the dust content from ١٠ to ٢٥ percent resulted in only a small decrease in the compressive strength of concrete.

The effect of fine materials in crushed rocks as fine aggregate was studied by **Elizzi *et al*** [٤١]. They noticed that up to a level of ١٥ percent, the compressive and flexural strengths increase with increasing the percentage of the fine materials. Also, the workability and length change (expansion and shrinkage) are not affected much by the increase of fine materials. **Bonavetti** and **Irassar** [٤٢] investigated the effect of stone dust content in fine aggregate on the strength of concrete. The results showed that the gain of concrete strength was attributable to the acceleration of the cement hydration at the early ages due to the effect of the stone dust. At the later ages, no detrimental effects were observed. **Hughes** and **Ash** [٤٣] have reported that the presence of dust in the fine aggregate can be beneficial for low strength concretes probably because of its ability to modify the structure of the cement paste, but it has little effect on high strength concretes.

2.4 Properties of CKD

The properties of CKD vary from cement plant to another depending in great part on the cement making process and the quality of the raw materials. The chemical analysis of CKD is shown in Table (٢-١) as reported by some previous studies [٤٧, ٤٨, ٤٩, ٥٠]. For the purpose of comparison, typical compositions of ordinary Portland cement and other waste materials having cementitious properties such as fly ash and blast furnace slag are included in this table.

Table (2-1): Composition of CKD and other cementitious materials

Oxide %	Cement kiln dust (CKD)				Cementitious materials		
	Ravindra (47)	Hasson (48)	Shoaib (49)	Al-Zubaidy (50)	Cement	Slag (3)	Fly ash (3)
SiO_2	12.2	14.5	12	14.1	20.8	30-39	34-63
Al_2O_3	5.8	2.0	1.1	4.7	6.1	7-26	13-36
Fe_2O_3	2.3	3.0	2.5	2.0	3.2	11-45	1-25
CaO	42.7	44.9	49.8	40.2	61.3	30-48	0.2-40
MgO	1.3	-	1.9	2.8	4.4	1-21	0.1-5
Na_2O	0.8	2.3	3.9	1.7	-	0.2-1.2	0.1-6
K_2O	4.3	4.1	2.6	3.2	-	0.2-1.5	0.1-2
SO_3	6.5	3.1	6.3	5.8	2.4	-	0.05-5
Cl	-	-	6.8	1.8	-	-	-
L.O.I.	22.1	20.3	17.9	24.3	1.8	-	0.8-15

The geological and physical properties of CKD are shown in Tables (٢-٢) and (٢-٣) respectively.

Table (2-2): Geological properties of CKD [50]

Property	
Colour	Light brown
Surface texture	Smooth
Surface shape	Semi-Spherical particles
Clear from organic materials and other deteriorous substances	

Table (2-3): Physical properties of CKD [46]

Property	Value
Passing 30 μm	75%
Maximum particle size	300 μm
Specific surface	4550-9000 (cm^2/gm)
Specific gravity	2.6-2.8

2.5 Uses of CKD

In the construction industry, CKD is used for various engineering purposes, such as a filler and activating agent for rubber compounds [٥١, ٥٢], brick industry [٥٣,٥٤], sand stabilizer [٤٦, ٥٤, ٥٥, ٥٦,٥٧] and mineral filler in asphalt pavements [٤٦, ٥٨]. However, the use of CKD in one or more of these purposes may be a better solution than landfilling while avoiding the associated costs and liabilities [٤٥].

The use of CKD in the manufacture of concrete was studied in some earlier experimental works [٤٧,٥٠, ٦٠] and recently by other researches [٤٨, ٤٩, ٥٩]. **Ravindraraja** [٤٧] has studied the effects of CKD as a partial replacement of ordinary Portland cement on some properties of concrete. CKD contents used ranged from ٠ to ٤٥ percent by weight of cement, and the water content of mixes was adjusted to obtain the same workability.The results obtained with the fresh concrete showed that, when the amount of CKD was increased in the mix, the water demand to maintain the same workability has increased. This could be due to the increased proportion of the finer particles in the modified mixes.

The results of the strength showed that, as the amount of CKD increased, the compressive strength decreases at any particular age. According to the strength development with age expressed as a percentage of its ٢٨-day strength, the study showed that, at the early ages, the hydration of the cementitious particles in CKD may occur at a faster rate than the cement particles. This could be due to that CKD particles are finer than cement. Generally, the ٢٨ days compressive strength of the concrete was decreased by ٣٧ percent when ٤٥ percent of Portland cement was replaced by CKD.

It can be concluded that the splitting tensile and flexural strengths decrease with the increase of cement replacement. The ratios of flexural and tensile strengths to compressive strength are found to improve up to ٢٥ percent for the modified mix. The author has reported that, if CKD is an inert filler, the drop in strength will be very much more than the observed amount; therefore, CKD contains a certain degree of cementitious property which contributes to the development of strength. Also, it was reported that Portland cement in concrete could be safely replaced by up to ١٥ percent of CKD and this can result in savings in construction cost.

Hasson *et al.* [٤٨] have investigated the influence of CKD as a partial replacement of ordinary Portland cement on some properties of concrete. The percentages of cement replacement were ١٥ to ٣٥ percent. A water to cement ratio of ٠.٥٥ was used and kept constant for each mix. This study proved that the replacement of cement by CKD has resulted in a decrease in compressive strength of concrete. The magnitude of strength reduction was increased with the increase in the cement replacement.

It could be noticed that when ٣٥ percent of the cement was replaced by CKD, the compressive strength of concrete was reduced by about ٣٢ and ٢٦ percent for ٢٨ and ٩٠ days respectively. At ٩٠ days, the gradually increasing in compressive strength could be attributed to the reaction between the cement hydration products and CKD during the hydration process.

The results also indicated that the water absorption of concrete was increased by the proportion of CKD increase. But the thermal conductivity was lowered by the increase in the percentage of CKD, especially for longer ages, which leads toward improving thermal insulation. Generally, it could be concluded that up to a level of ٢٥ percent of cement replacement, CKD could be used in the concrete industry.

Shoaib *et al*. [٤٩] studied the effect of CKD as a partial replacement for portland cement on the mechanical behaviour of concrete. The percentages of replacement of CKD were ٠, ١٠, ٢٠, ٣٠ and ٤٠ percent. Results of compressive strength for the concrete specimens showed that the addition of CKD to the mix resulted in decreasing the compressive strength, especially with high CKD percentages. This reduction was due to the presence of considerable amounts of alkalies in CKD. The results also showed that the tensile strength of concrete decreases with increasing the amounts of CKD in the mix. Generally, it was observed that for (١٠-٢٠) percent of CKD replacement, the compressive strength was slightly reduced. However, at this range, CKD could be used in concrete.

The authors have also reported that the direct mixing of CKD in concrete is more effective than the recycling of CKD with cement raw materials, which forms unfavored clinker phase during the firing in cement kilns. This can be attributed to the effect of high alkalinity of CKD on the nature of clinker phases.

El-Didamony *et al*. [٥٩] studied the effect of various amounts of silica fume with ٥ percent CKD on the physico-mechanical properties of slag cement. The results reveal that the increase of silica fume tends to increase the mixing water and the setting time (initial and final). On the other hand, the compressive strength of cement paste decreases with silica fume due to the increase of mixing water and the porosity of the paste. It can be concluded that CKD can be used as an activator for hydration of cement paste.

It is observed that some of CKD can be used to evaluate one potential application, that is, utilization of CKD in combination with cement in cement plants. **Daugherty** and **Funnell** [٦٠] studied the effect of CKD as part of the finished product of the cement plant. They reported that the ability to use CKD in the finished cement product would:

١. Provide a method of dust disposal with less capital and less energy requirement.

٢. Use the energy investment in the dust without requirement of additional energy expenditure, and

٣. Increase production capacity of plants without large capital expenditures.

They used CKD specimens from ١٨ locations. Each CKD specimen was used and evaluated with the cement produced. In each instance, the performance of a ٩٥٪ cement to ٥٪ CKD blend and a ٩٠٪ cement to ١٠٪ CKD blend were compared to the performance of the base cement. Out of ١٨ CKD specimens tested, ١٠ gain beneficial effects to strength development in concrete through one year of testing and, therefore, showed promise of being usable for blending with cement. The remaining ٨ specimens showed detrimental effects on concrete strength.

Overall findings of the study have shown that CKD has some cementitious properties of its own, and at the same time, components of CKD that are not cementitious in their own will react with material in the concrete to form cementitious compounds. Therefore, much more work will be necessary before a specification can be proposed.

Al-Zubaidy and **Kadhim** [٥٠] have investigated the properties of concrete and mortar when CKD was used as a partial and full replacement for fine aggregate. In this investigation, different mix proportions were used for the concrete and mortar, with percentages of replacement of ٠, ٢٥, ٥٠, ٧٥ and ١٠٠ by weight of fine aggregate. The water – cement ratio for each mix proportion was kept constant.

The results showed that the workability of the mixes decreased with increasing CKD content, especially at high levels of replacement. On the other hand, the ٢٨ days compressive strength decreased with the increase in percentage addition of CKD. The total replacement of fine aggregate by CKD significantly reduces the compressive strength of both concrete and mortar at all mix proportions. However, the reduction magnitude in the compressive strength at the total replacement was about ٥٣ and ٦٩ percent in cement mortar and concrete respectively.

It was reported that CKD up to ٢٥ percent do not significantly affect the workability and compressive strength and therefore, up to this level, the fine aggregate could be replaced by CKD in cement mortar and concrete.

It should be noticed that the difference between the work contained in this study and that in the previous studies is that, many tests such as ultrasonic pulse velocity, drying shrinkage and expansion have adopted in this work. Furthermore, different curing ages, mix proportions and percentages of CKD were investigated.

CHAPTER 3

EXPERIMENTAL WORK

٣.١ Introduction

In this chapter, the details of the experimental program of the study are presented. These include the materials used, specimens preparation and the tests carried out.

٣.٢ Materials

٣.٢.١ Cement

Ordinary Portland cement manufactured by the New Cement Plant of Kufa is used throughout this study conforming to Iraqi specification (IOS ٥: ١٩٨٤) [٦١]. The physical and chemical properties of this cement are given in Tables (A-١) and (A-٢).

٣.٢.٢ Fine Aggregate

Al-Ukhaidher sand was used in the experimental work. The physical and chemical properties of the sand are given in Table (A-٣). Its grading was within the limits required by Iraqi specification (IOS ٤٥: ١٩٨٤) [٦٢], Zone (٣).

٣.٢.٣ Coarse Aggregate

The gravel used throughout the research was brought from Al-Nebaee area. It was sieved on ٢٠ mm sieve. Table (A-٤) shows the physical and chemical properties of the gravel. The table also includes the limits specified by IOS ٤٥: ١٩٨٤ [٦٢].

٣.٢.٤ Cement Kiln Dust (CKD)

CKD used in this study was supplied by the New Cement Plant of Kufa. The dust was collected from electrostatic precipitators at the kiln and then stored in a dry place. The physical and chemical analysis of CKD are shown in Table (٣-١). For the purpose of comparison, the chemical analysis of the cement used in this study is included in this table.

٣.٢.٥ Water

Ordinary tap water was used throughout this work for both making and curing the specimens.

Table (٣-١): Chemical and physical analysis of CKD

Chemical analysis (%)	CKD	Cement
$SiO_٢$	١٩.٧٨	٢٠.٨٠
$Fe_٢O_٣$	٣.١٠	٣.٢٠
$Al_٢O_٣$	٣.٥٦	٦.١٢
CaO	٤٣.١١	٦١.٢٦
MgO	٣.٣٠	٤.٤٠
$SO_٣$	٤.٢٠	٢.٣٣
$Na_٢O$	١.٩١	-
$K_٢O$	٣.٧٢	-
Cl	١.٦٧	-
L.O.I	١٧.٦٠	١.٧٥
Free lime	١.٣٠	٠.٧٦
I.R.	١٠.٢٦	٠.٦١
Physical analysis		
Specific gravity	٢.٦٧	٣.١٥
Specific surface ($cm^٢/gm$)	٤٨١٠	٣٠٦٠

٣.٣ Outline of the Experimental Program

The experimental program of this study was conducted on specimens of concrete and mortar. Concrete specimens were prepared for compressive strength, modulus of rupture, splitting tensile strength, density and ultrasonic pulse velocity. The compressive strength, drying shrinkage and expansion measurements were carried out on mortar specimens. Different mix proportions and percentages of CKD were used to investigate these properties.

٣.٤ Details of Mixes

٣.٤.١ Concrete Mixes

According to the strength level and type of replacement, concrete mixes were divided into four series (CRA, CRB, SRA and SRB) having two control mixes of ١: ٢: ٤ and ١: ١.٥: ٣ (cement: sand: gravel by weight).

In the first two series, the partial replacement of ordinary Portland cement by CKD was made. In the remaining two series, CKD was used as sand replacement. Five mixes were made in each series using different percentages of CKD. Details of concrete mixes are shown in Tables (٣-٢) and (٣-٣).

Table (٣-٢): Details of concrete mixes (cement replacement)

Mix series	Specimen mark	CKD by weight of cement%	Mix designation CKD: cement: sand: gravel
CRA	CRA-٠	٠	٠:١:٢:٤
	CRA-١٠	١٠	٠.١:٠.٩:٢:٤
	CRA-٢٠	٢٠	٠.٢:٠.٨:٢:٤
	CRA-٣٠	٣٠	٠.٣:٠.٧:٢:٤
	CRA-٤٠	٤٠	٠.٤:٠.٦:٢:٤
	CRA-٥٠	٥٠	٠.٥:٠.٥:٢:٤
CRB	CRB-٠	٠	٠:١:١.٥:٣
	CRB-١٠	١٠	٠.١:٠.٩:١.٥:٣
	CRB-٢٠	٢٠	٠.٢:٠.٨:١.٥:٣
	CRB-٣٠	٣٠	٠.٣:٠.٧:١.٥:٣
	CRB-٤٠	٤٠	٠.٤:٠.٦:١.٥:٣
	CRB-٥٠	٥٠	٠.٥:٠.٥:١.٥:٣

Table (٣-٣): Details of concrete mixes (sand replacement)

Mix series	Specimen mark	CKD by weight of sand %	Mix designation CKD: cement: sand: gravel
SRA	SRA-٠	٠	٠:١:٢:٤
	SRA-١٠	١٠	٠.٢:١:١.٨:٤
	SRA-٢٠	٢٠	٠.٤:١:١.٦:٤
	SRA-٣٠	٣٠	٠.٦:١:١.٤:٤
	SRA-٤٠	٤٠	٠.٨:١:١.٢:٤
	SRA-٥٠	٥٠	١:١:١:٤
SRB	SRB-٠	٠	٠:١:١.٥:٣
	SRB-١٠	١٠	٠.١٥:١:١.٣٥:٣
	SRB-٢٠	٢٠	٠.٣:١:١.٢:٣
	SRB-٣٠	٣٠	٠.٤٥:١:١.٠٥:٣
	SRB-٤٠	٤٠	٠.٦:١:٠.٩:٣
	SRB-٥٠	٥٠	٠.٧٥:١:٠.٧٥:٣

٣.٤.٢ Mortar Mixes

Four series of mortar specimens (CRL, CRM, SRL and SRM) were made to study the effect of CKD on the compressive strength, shrinkage and expansion. Two types of control mixes were also made which have cement / sand ratios of ١: ٢ and ١: ٣ by weight.

CKD was used as a partial replacement of cement in the first two series. While in the second two series, CKD was used as sand replacement. For each series, four percentages of CKD were used : ١٠, ٢٠, ٣٠ and ٤٠ percent. Details of these mixes are shown in Tables (٣-٤) and (٣-٥).

Table (٣-٤): Details of mortar mixes (cement replacement)

Mix series	Specimen mark	CKD by weight of cement %	Mix designation CKD: cement: sand: gravel
CRL	CRL-٠	٠	٠:١:٣
	CRL-١٠	١٠	٠.١:٠.٩:٣
	CRL-٢٠	٢٠	٠.٢:٠.٨:٣
	CRL-٣٠	٣٠	٠.٣:٠.٧:٣
	CRL-٤٠	٤٠	٠.٤:٠.٦:٣
CRM	CRM-٠	٠	٠:١:٢
	CRM-١٠	١٠	٠.١:٠.٩:٢
	CRM-٢٠	٢٠	٠.٢:٠.٨:٢
	CRM-٣٠	٣٠	٠.٣:٠.٧:٢
	CRM-٤٠	٤٠	٠.٤:٠.٦:٢

Table (٣-٥): Details of mortar mixes (sand replacement)

Mix series	Specimen mark	CKD by weight of sand %	Mix designation CKD: cement: sand: gravel
SRL	SRL-٠	٠	٠:١:٣
	SRL-١٠	١٠	٠.٣:١:٢.٧
	SRL-٢٠	٢٠	٠.٦:١:٢.٤
	SRL-٣٠	٣٠	٠.٩:١:٢.١
	SRL-٤٠	٤٠	١.٢:١:١.٨
SRM	SRM-٠	٠	٠:١:٢
	SRM-١٠	١٠	٠.٢:١:١.٨
	SRM-٢٠	٢٠	٠.٤:١:١.٦
	SRM-٣٠	٣٠	٠.٦:١:١.٤
	SRM-٤٠	٤٠	٠.٨:١:١.٢

٣.٥ Specimens Preparation

٣.٥.١ Mixing

A horizontal pan-type mixer of ٠.١ m^{٣} capacity was used for mixing concrete. The interior surface of the mixer was cleaned and moistened before it was used. The aggregate, cement and CKD were first mixed dry for ٦٠ sec., then the water was added and mixed for another ٤ min. to get homogeneous fresh concrete mixes.

٣.٥.٢ Casting and Compaction

After mixing, the concrete and mortar were poured into the moulds and compacted by using a vibrating table. The excess mortar was cut and removed with a trowel from the top of the specimens.

٣.٥.٣ Curing

After casting, all specimens were covered with polyethylene sheets and left in the laboratory for ٢٤ hrs. The specimens were then demoulded carefully and cured in different environments as required.

Specimens prepared for compressive strength, splitting tensile strength and modulus of rupture, density, ultrasonic pulse velocity and expansion strain were stored in the tap water tanks until testing age.

Specimens prepared for drying shrinkage test were stored in the tap water until the age of ٧ days, then they were taken out and stored in a dry place inside the laboratory until the age of ١٨٠ days.

٣.٦ Testing Procedures

٣.٦.١ Slump Test

The slump of fresh concrete mixes was conducted according to ASTM C١٤٣ [٦٣].

٣.٦.٢ Flow Table Test

The flow table test of fresh mortar mixes was determined according to ASTM C٢٣٠ [٦٤].

٣.٦.٣ Compressive Strength Test

Compressive strength of concrete specimens was carried out on (١٥٠ mm) cubes according to B.S. ١٨٨١: Part ٤ [٦٥], using a digital testing machine of ٢٠٠٠ kN maximum capacity. For mortar specimens, the compressive strength tests were conducted on (٥٠ mm) cubes according to ASTM C ١٠٩ [٦٧] by using ٢٠٠ kN capacity testing machine.

The compressive strength of concrete specimens was tested at the ages of ٧, ٢٨, ٩٠ and ١٨٠ days, whereas the mortar specimens were tested at the ages of ٧, ٢٨ and ٩٠ days. The average of three specimens in each age was adopted.

٣.٦.٤ Modulus of Rupture Test

Three points flexure tests were performed on three (١٠٠ × ١٠٠ × ٤٠٠ mm) prisms with a span of ٣٠٠ mm using the machine meeting the requirements of ASTM C٢٩٣ [٦٧]. The specimens were tested at the ages of ٢٨ and ٩٠ days.

٣.٦.٥ Splitting Tensile Strength Test

The splitting tensile strength test was determined according to the procedure outlined in ASTM C٤٩٦ [٦٨], using (١٠٠ × ٢٠٠ mm) cylinders. The specimens were tested at the ages of ٢٨ and ٩٠ days. Each strength value is the average of the strength of three specimens.

٣.٦.٦ Density Test

(١٠٠ × ٢٠٠ mm) cylinders were used to determine the density of concrete specimens at the age of ٢٨ days. The cylinders were weighted to the nearest (٠.١ gm) and the average of the three specimens was adopted.

٣.٦.٧ Ultrasonic Pulse Velocity Test

The velocity of the ultrasonic pulse of the concrete specimens was determined before finding the crushing compressive strength.This test was carried out according to B.S. ١٨٨١: Part ٢٠٣ [٦٩].Portable Ultrasonic Concrete Tester shown in Plate(٣-١) was used for this purpose. Calibration of the Concrete Tester was done before testing to check the accuracy of the transit time measurements. This was achieved by a calibration bar or reference bar. A thin layer of grease was applied to act as a couplant and to increase the transmitted energy. The pulse travelling path length was measured accurately and the time of its travelling was recorded to the order of ٠.٠١ μ sec.

The concrete cubes at each age were tested immediately after removing them from curing water.The pulse velocity was determined as follows:

V=L/T …………..(٣-١)

where:

V = ultrasonic pulse velocity, km/sec.

L = path length, km.

T = transit time,sec.

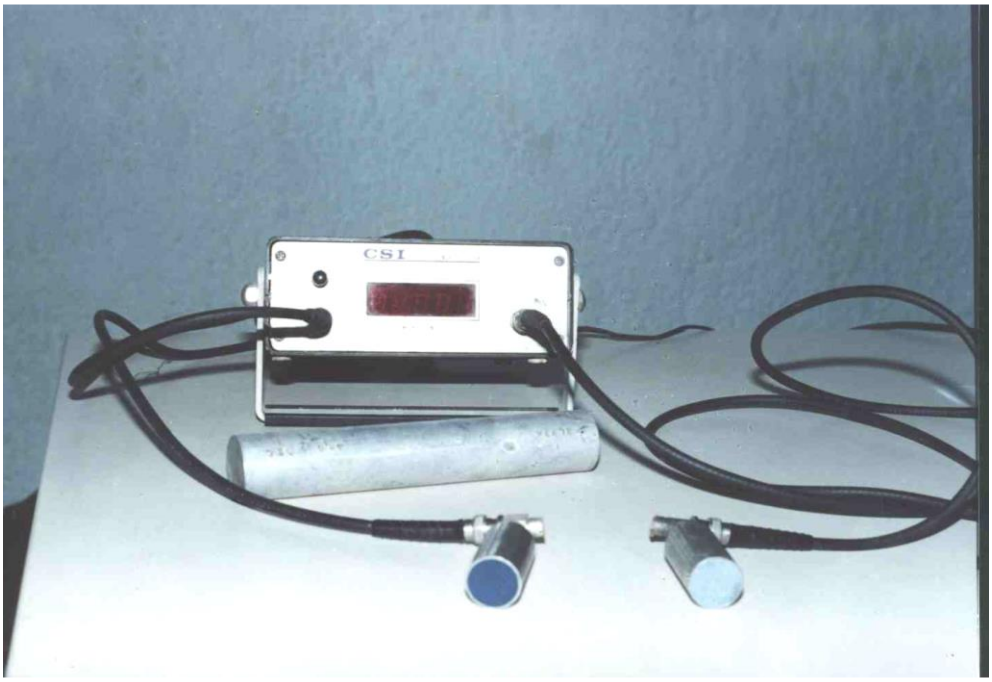

Plate (٣-١): Ultrasonic pulse velocity testing device.

٣.٦.٨ Drying Shrinkage and Expansion Tests

Two series of mortar specimens in addition to a control mix of ١: ٣ (cement: sand) were prepared for shrinkage and expansion tests. For each mix, six prisms of (٢٥×٢٥×٢٨٥ mm) were casted. Three prisms were kept in water and used for expansion purposes. The remaining three prisms were used for drying shrinkage which were kept in laboratory conditions after they had been cured in water for ٧ days. Stainless steel gage studs were used and fixed on each two ends of each specimen. The length change of the specimens was measured by means of a length comparator device as shown in Plate(٣-٢), satisfying the requirements of ASTM C١٥٧ [٧٠]. The accuracy of the dial gage of the measuring device is ٠.٠٠٢mm. The length change of the specimens was measured at the ages of ٣, ٧, ١٤ , ٢٠, ٢٨, ٦٠, ٩٠, ١٢٠ and ١٨٠ days. At any age the change of specimen lengh was determined as follows:

$$\Delta L = \frac{R - R_o}{L} \times 100$$ …………(٣-٢)

where:

ΔL = length change of the specimen,%
L = initial length of the specimen,mm.
R = gage reading, mm.
R_o = initial gage reading, mm.

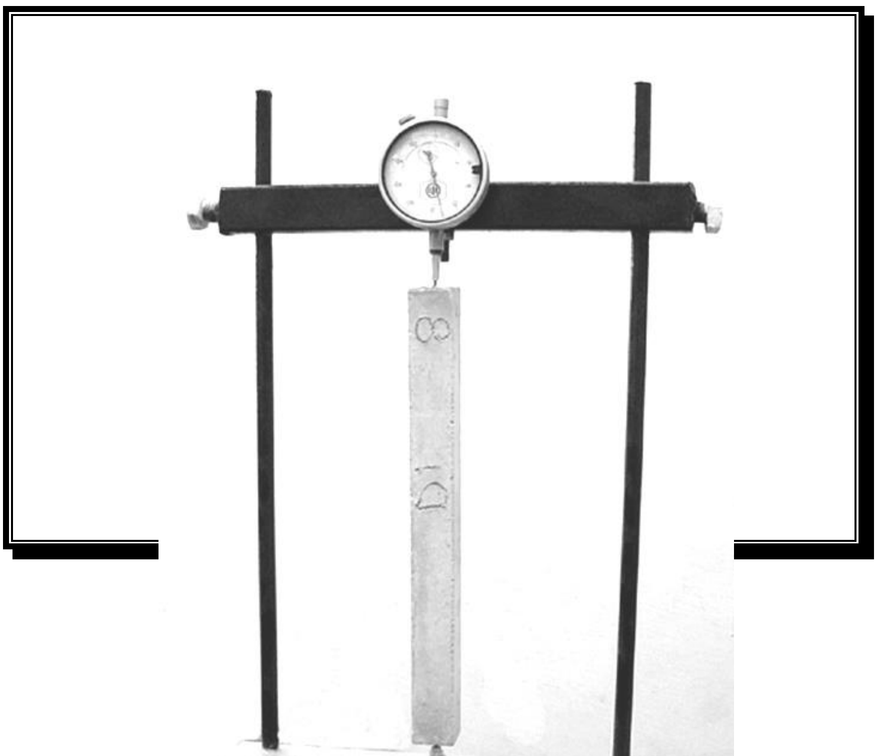

Plate (٣-٢) Length change testing device.

CHAPTER 4

RESULTS AND DISCUSSION

٤.١ Introduction

In this chapter, the results of the tests described in chapter three are presented and discussed. To condense the data, only the average values are provided in form of tables and figures.

٤.٢ Characteristics of CKD

The chemical and physical properties of CKD used in this study are given in Table (٣-١). It can be seen that the sulphur trioxide and alkali contents of CKD are greater that those of cement. Sulphur trioxide is originated from the clay of raw material and the fuel used in cement burning, while the source of alkalies in CKD is both the raw materials and the fuel [٥٥]. The analysis of CKD also shows a considerable amount of loss on ignition. Generally, the high ignition loss is associated with the presence of carbonaceous matter [٥].

The physical analysis of CKD shows that the specific gravity is about ٢.٦٧, which is less than that of Portland cement (specific gravity of ٣.١٥). Therefore, any replacement of cement by CKD on the basis of weight will increase the volume of the mix when compared with the control mix. It can be seen also that the specific surface of CKD is about

٤٨١٠ (cm٢/gm). This indicates that CKD samples contain more finer particles than the cement samples. It can be noticed that the general appearance of CKD is light brown in colour. The colour varies from patch to patch from the same source.

٤.٣ Workability Test Results

The workability of concrete mixes used in this study was measured by slump test. The slump and W/C or W/C+CKD ratio for all mixes are shown in Tables (٤-١) and (٤-٢). When CKD was used as cement replacement (series CRA and CRB), the W/C+CKD ratio was kept constant. While the W/C ratios were adjusted to have workable mixes with (٧٥±١٥mm) slump when CKD was used as a partial replacement of sand (series SRA and SRB).

Table (٤-١): Slump test results for concrete mixes when CKD is used as partial cement replacement.

Mix Series	Specimen mark	W/C+CKD ratio	Slump (mm)
CRA	CRA-٠	٠.٥٧	٨٠
	CRA-١٠	٠.٥٧	٨٥
	CRA-٢٠	٠.٥٧	٧٠
	CRA-٣٠	٠.٥٧	٦٥
	CRA-٤٠	٠.٥٧	٦٠
	CRA-٥٠	٠.٥٧	٥٠
CRB	CRB-٠	٠.٤٨	٧٠
	CRB-١٠	٠.٤٨	٦٥
	CRB-٢٠	٠.٤٨	٦٥
	CRB-٣٠	٠.٤٨	٦٠
	CRB-٤٠	٠.٤٨	٥٠
	CRB-٥٠	٠.٤٨	٤٥

Table (٤-٢): Variations in the W/C ratios for concrete mixes when CKD is used as a percentage of sand.

Mix Series	Specimen mark	W/C ratio	Slump (mm)
SRA	SRA-٠	٠.٥٧	٨٠
	SRA-١٠	٠.٥٨	٧٥
	SRA-٢٠	٠.٥٩	٦٥
	SRA-٣٠	٠.٦١	٧٠
	SRA-٤٠	٠.٦٤	٧٥
	SRA-٥٠	٠.٧٠	٦٠
SRB	SRB-٠	٠.٤٨	٧٠
	SRB-١٠	٠.٤٩	٦٠
	SRB-٢٠	٠.٥٢	٨٥
	SRB-٣٠	٠.٥٤	٧٥
	SRB-٤٠	٠.٥٨	٦٠
	SRB-٥٠	٠.٦٣	٨٠

For cement mortar, the flow table test was adopted for measuring the workability of the mixes. The W/C+CKD ratio was kept constant in cement replacement which were ٠.٥٣ and ٠.٤٢ in series CRL and CRM respectively. For sand replacement (series SRL and SRM), the W/C ratios were adjusted to maintain a flow of (١٠٠±١٠) percent.

From Table (٤-١), it can be seen that the workability of concrete or mortar mixes is slightly affected when CKD is used as cement replacement.

The results indicate also that when CKD is used as partial substitution of sand, the water demand to produce the same workability is a function of the percentage of CKD used and increases with the increase in CKD content. It can be noticed that with up to ٢٠ % of CKD used as sand replacement, the water demand is slightly higher than that of the control mix. Such demand increases rapidly when more than ٢٠ % of CKD is used. This increase could be due to the increase in the proportion of the fine particles in the modified mixes [٤٧]. However, excessive quantities of fine dust causes an increase in the surface area of the particles which will result in an increase in the amount of water required to wet the particles [٣٩].

٤.٤ Compressive Strength Test Results

٤.٤.١ Compressive Strength of Concrete

The compressive strength for both cement and sand replacement by CKD of concrete specimens at ٧, ٢٨, ٩٠ and ١٨٠ days age are discussed in the following sections.

٤.٤.١.١ Replacing Cement by CKD

Table (٤-٣) and Figs (٤-١) and (٤-٢) show the effect of replacing cement by CKD on the compressive strength of series CRA and CRB. The results show that replacing cement by CKD reduces the compressive strength of concrete samples, especially at high values of replacement. Up to ١٠٪ of CKD replacement, the reduction in the ٢٨ days compressive strength was about ٨.٤ and ٩.٨ percent in series CRA and CRB respectively.

Table (٤-٣): Compressive strength test results of concrete when CKD is used as a partial replacement of cement.

Mix Series	Specimen mark	Compressive strength (MPa)			
		٧ days	٢٨ days	٩٠ days	١٨٠ days
CRA	CRA-٠	١٩.٢٤	٢٨.١١	٣٥.٨٠	٣٧.٧٠
	CRA-١٠	١٧.٧٢	٢٥.٧٥	٣٣.٨٥	٣٦.٧٨
	CRA-٢٠	١٦.٩١	٢١.٣١	٢٩.٣٦	٣٤.٥٠
	CRA-٣٠	١٥.٠٠	١٩.٢٦	٢٧.٩٦	٣١.١١
	CRA-٤٠	١٢.٦٢	١٧.١٥	٢٣.٩١	٢٤.٩٠
	CRA-٥٠	١١.٧٧	١٥.٠٣	١٩.٣٣	٢١.٥١
CRB	CRB-٠	٢٤.٧٥	٣٤.٢٤	٤٠.٤٢	٣٩.٢٠
	CRB-١٠	٢١.٩٠	٣٠.٨٨	٣٧.٧١	٣٩.٨٥
	CRB-٢٠	٢١.٣٤	٢٤.٨٢	٣٦.١٤	٣٧.٠٥
	CRB-٣٠	١٧.٥٠	٢٢.٩٨	٢٩.٩٠	٣٤.٣٣
	CRB-٤٠	١٦.١٥	٢٢.٠٠	٢٧.٢٠	٣٠.١٠
	CRB-٥٠	١٤.٧٤	١٩.١٣	٢٤.٨٦	٢٦.٠٨

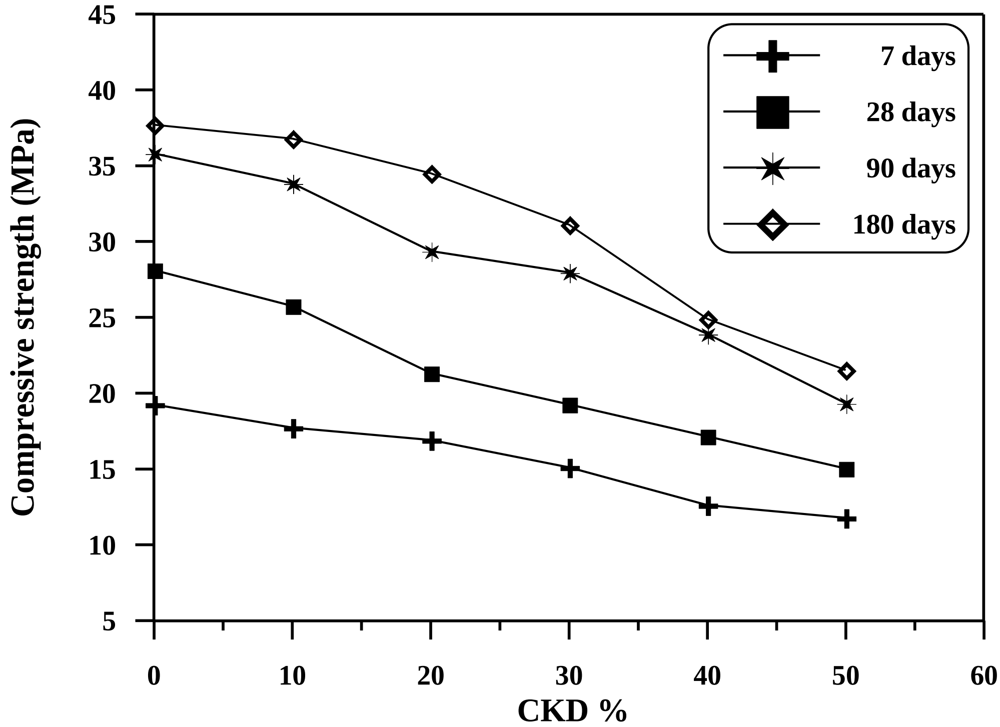

Fig.(٤-١): Effect of replacing cement by CKD on the compressive strength of concrete (series CRA).

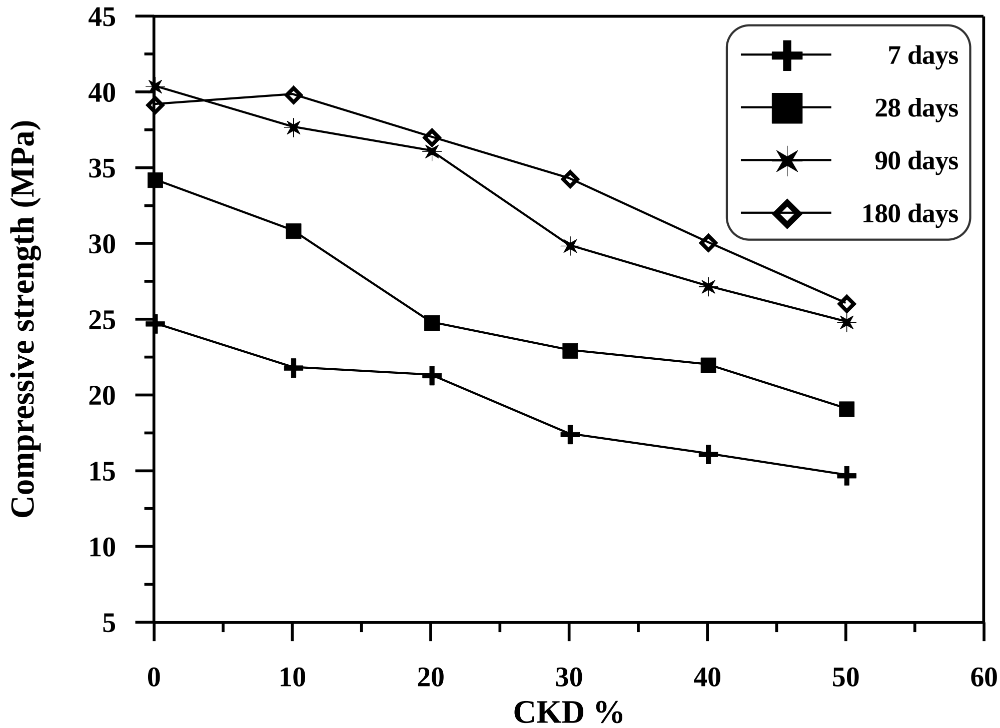

Fig.(٤-٢): Effect of replacing cement by CKD on the compressive strength of concrete (series CRB).

This reduction in compressive strength can be attributed to the reduction in the cement content of the mix, which is mainly responsible for the strength development. In addition, the presence of chloride in CKD may cause a sort of crystallization of hydration products which results in an opening of the pore system of the hardened gel structure leading to a reduction in strength [٤٩]. However, the chloride ions of CKD have a role in chemical reactions similar to that of sulphate ions and yield chloro-aluminate hydrate $٣CaO.Al_{٢}O_{٣}.CaCl_{٢}.١٢H_{٢}O$ which is identical to $٣CaO.Al_{٢}O_{٣}.CaSO_{٤}.١٢H_{٢}O$ [٤٩]. It was reported also that the presence of significant amounts of alkalis makes the structure of the hydration products of cement hetrogeneous and lowers the strength [٧١].

The compressive strength development with time for up to ٦ months is shown in Figs (٤-٣) and (٤-٤). It can be noticed that the percentage of strength reduction decreases with age especially that of ١٠ and ٢٠ percent of CKD replacement. This is due to the presence of some cementitious compounds in CKD, which causes the increase in the amount of hydration products. Also, the accumulation in these products with time closes the available pore space which leads to decrease the total porosity and, finally, increase the compressive strength with age [٤٩]. At the same time, compounds of CKD that are not cementitious, will react with cement hydration products to form cementitious compounds [٦٠].

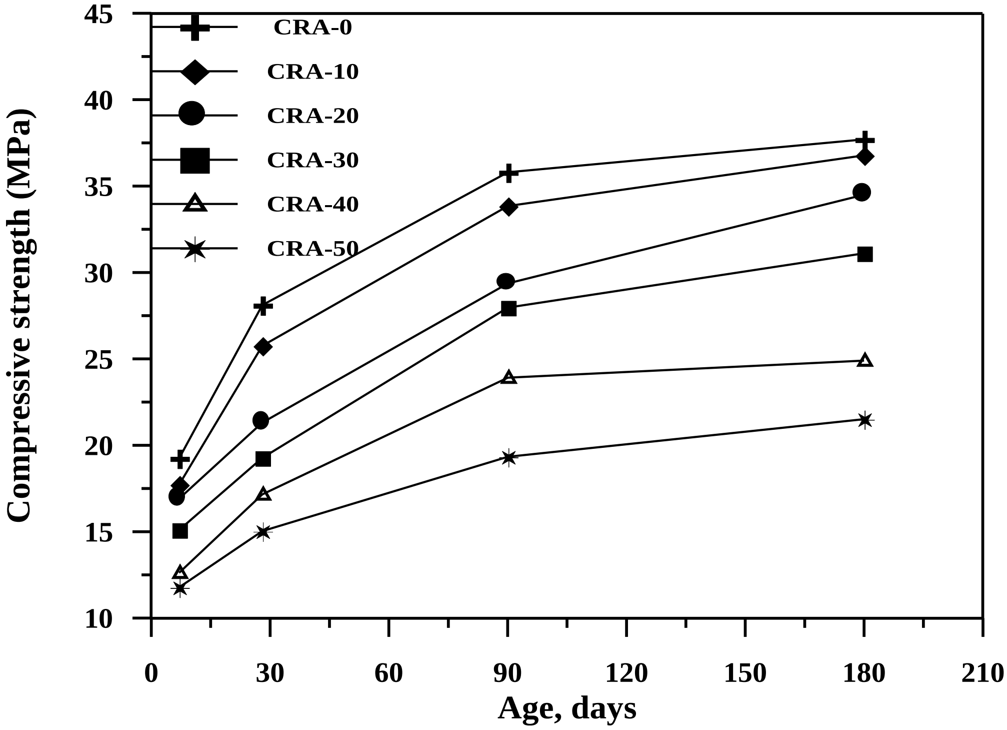

Fig.(٤-٣): Concrete compressive strength development for various percentages of cement replaced by CKD (series CRA).

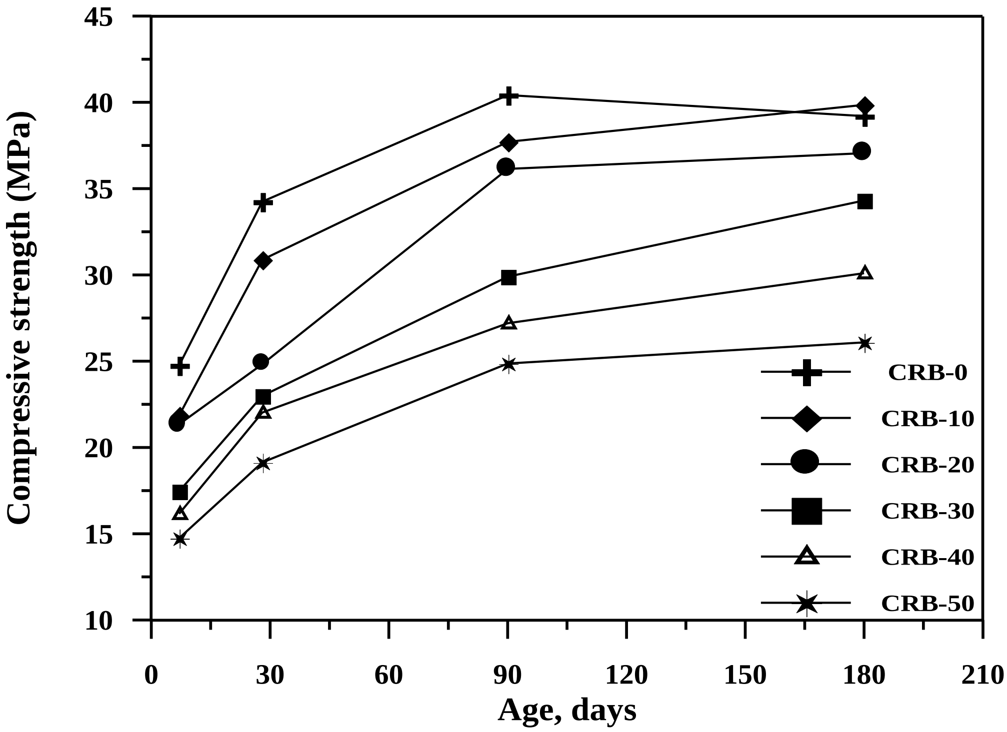

Fig.(٤-٤): Concrete compressive strength development for various percentages of cement replaced by CKD (series CRB).

٤.٤.١.٢ Replacing Sand by CKD

The compressive strength data obtained from replacing sand by CKD of series SRA and SRB are shown in Table (٤-٤) and plotted in Figs.(٤-٥) and (٤-٦).

Table (٤-٤): Compressive strength test results of concrete when CKD is used as a partial replacement of sand.

Mix Series	Specimen mark	Compressive strength (MPa)			
		٧ days	٢٨ days	٩٠ days	١٨٠ days
SRA	SRA-٠	١٩.٢٤	٢٨.١١	٣٥.٨٠	٣٧.٧٠
	SRA-١٠	٢٢.٣٦	٢٨.٩٨	٣٧.٥١	٣٨.٩٠
	SRA-٢٠	٢٤.٢٠	٣٠.٣٦	٣٨.٠٠	٤١.٤٩
	SRA-٣٠	٢٢.٨٠	٢٦.٧١	٣١.٦٨	٣٥.٢٠
	SRA-٤٠	٢٠.٨١	٢٥.٥٨	٢٩.٩١	٣١.٦٨
	SRA-٥٠	١٨.٦٢	٢٤.٠٠	٢٦.٤٨	٢٥.٨٠
SRB	SRB-٠	٢٤.٧٥	٣٤.٢٤	٤٠.٤٢	٣٩.٢٠
	SRB-١٠	٢٢.٠٨	٣٢.٩٤	٣٩.٨٨	٤١.٨٧
	SRB-٢٠	٢٣.٤٠	٣٠.٨٠	٣٨.٥٤	٣٩.٦٤
	SRB-٣٠	٢١.٨٥	٢٨.٧١	٣٤.٦٠	٣٧.٦٤
	SRB-٤٠	٢٠.٩١	٢٧.٣٨	٣١.٥٥	٣١.٩٤
	SRB-٥٠	١٩.٦٠	٢٤.١٣	٢٧.٠٨	٢٨.٣٨

Fig.(٤-٥) shows an improvement in the compressive strength as CKD percentage is increased, especially at the early ages (٧ days). Generally, beyond ٢٠٪ CKD replacement by sand, the strength at all ages started to decrease. However, the best strength has been achieved at series SRA which has ٢٠٪ of CKD. At this level, the increase in compressive strength is ٢٥.٥ and ٨ percent for ٧ and ٢٨ days respectively.

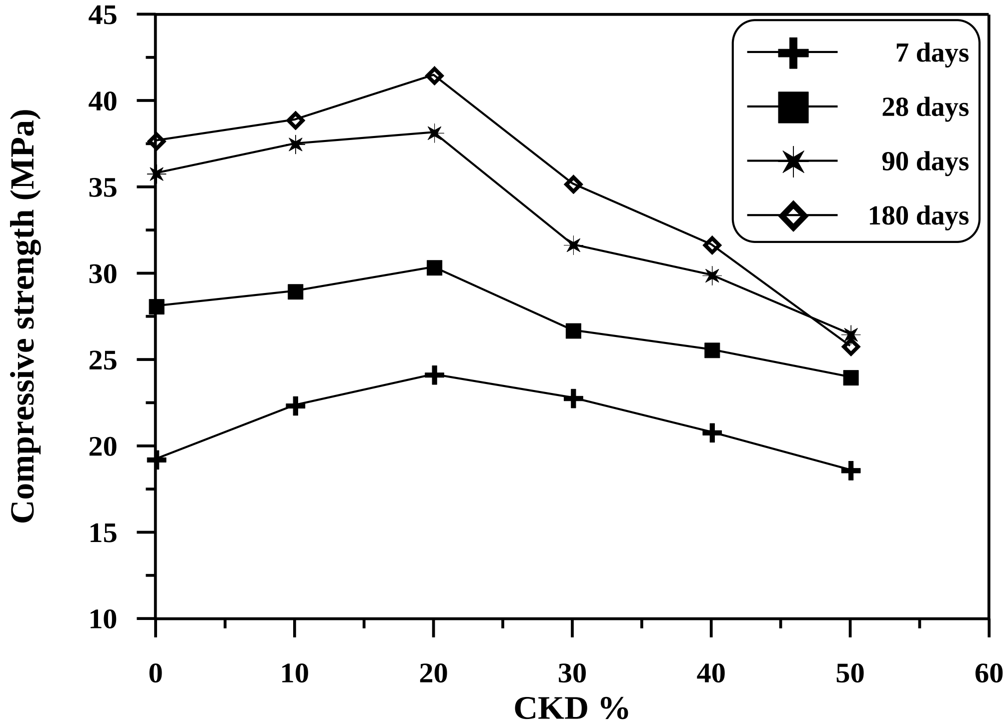

Fig.(٤-٥): Effect of replacing sand by CKD on the compressive strength of concrete (series SRA).

For series SRB, Fig.(٤-٦) shows that the compressive strength decreases with the increase in CKD content. In general, the strength started decreasing rapidly above the level of ٢٠٪ of CKD.

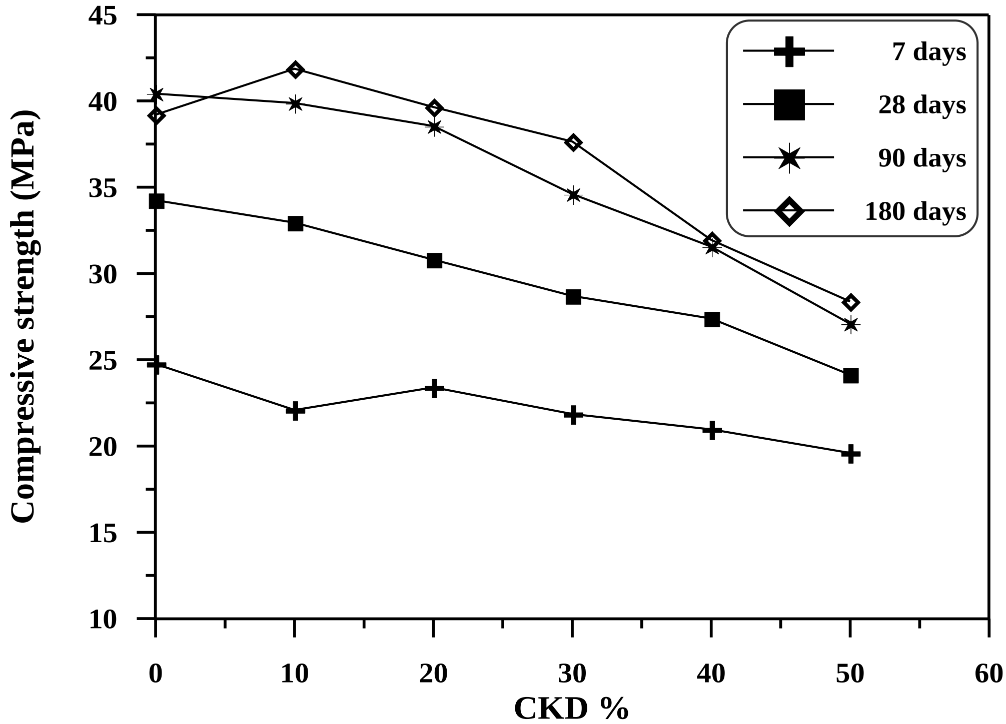

Fig.(٤-٦): Effect of replacing sand by CKD on the compressive strength of concrete (series SRB).

In series SRA, the increase in compressive strength is probably due to the filler effect of fine materials in CKD. However, the addition of fine materials as an admixture by replacing equal quantities of fine aggregate, increases the compressive strength of concrete, especially at the early ages [٦,١٢].

The development of compressive strength with time is shown in Figs.(٤-٧) and (٤-٨). Up to ٤٠٪ CKD replacement in series SRA, the compressive strength at ٧ days is higher than that of the control concrete (mix SRA-٠),see Fig.(٤-٧). Also, with ٣٠ and ٤٠ percent of CKD in this series, an increase in compressive strength of ١٨.٥ and ٨ percent respectively more than that of the control mix is observed, although the W/C ratio of these mixes is increased to obtain a workable mix. Since the increase in W/C ratio leads to decrease compressive strength, one would expect that the compressive strengths of concrete at these levels of replacement are less than that of the control mix. But, the results show that the strength increases even at ٤٠٪ of CKD. This may be attributed to the acceleration effect of CKD with alkalies, sulphates and chlorides which compensate the strength reduction due to the increase in W/C ratio. At the age of ٢٨ days and beyond, the compressive strength for mixes with ٣٠, ٤٠ and ٥٠ percent of CKD is lower than that of the control mix as shown in Fig.(٤-٧). However, at ١٠ and ٢٠ percent, the compressive strength is higher than that of the control mix at all ages.

For series SRB, Fig.(٤-٨) shows that up to ١٠٪ of CKD replacement, the compressive strength is generally comparable to or lower than that of the control mix, except for the age of ١٨٠ days.

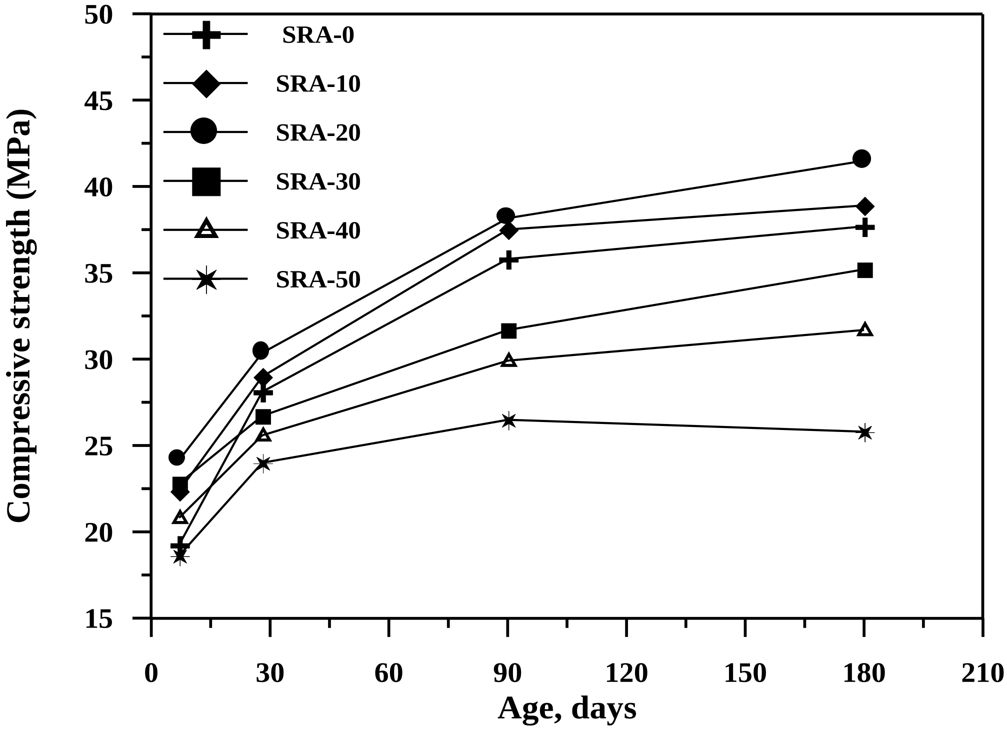

Fig.(٤-٧): Concrete compressive strength development for mixes of partial sand replacement by CKD (series SRA).

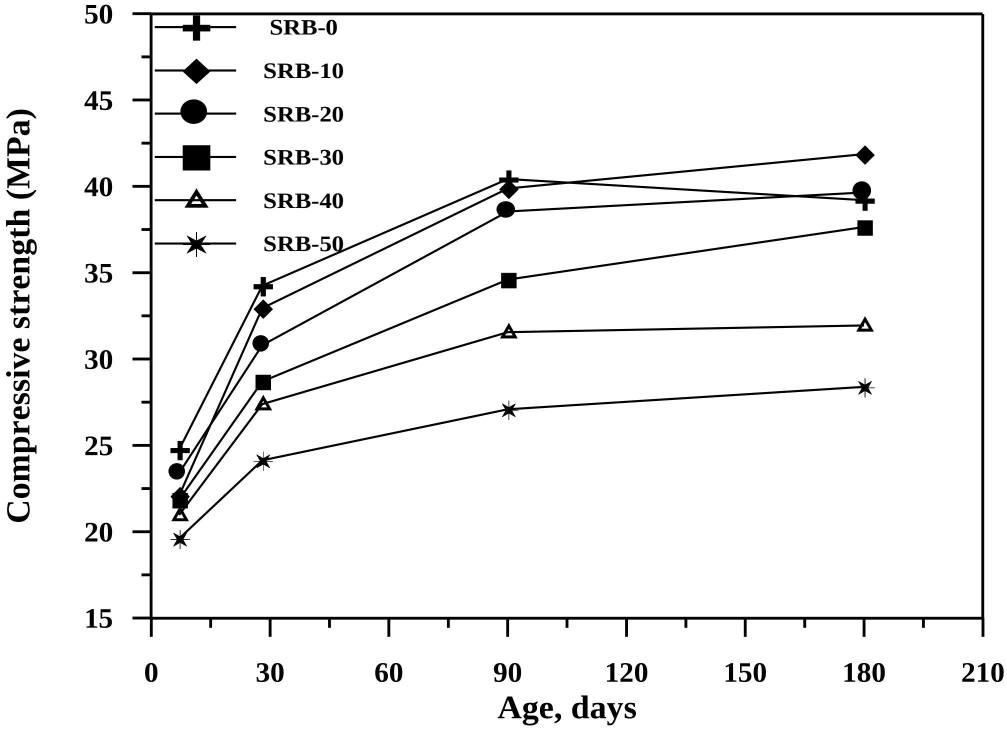

Fig.(٤-٨): Concrete compressive strength development for mixes of partial sand replacement by CKD (series SRB).

It can be stated that, at larger contents of CKD, the loss in compressive strength is due to presence of the fine material of CKD which causes a consequent increase in the water demand. From Table (٤-٢), when CKD is used as sand replacement, the water demand to maintain the same workability has increased rapidly. However, fine dust should not be presented in excessive quantities because, owing to their fineness and therefore large surface area, fine dust increases the amount of water necessary to wet all the particles in the mix and then, a reduction in strength will result [(٣٩)]. Also, the presence of alkalies and sulphates in CKD may have a role in the decrease of concrete strength.

It can be seen from Table (٤-٢) that the water content of mixes was adjusted to produce workable mixes when CKD was used as a percentage of sand. However, at ٥٠٪ of CKD replacement in series SRA, the decrease in ٢٨ days compressive strength of concrete is ١٤٪, whereas at this level of replacement, a significant decrease in compressive strength, which is about ٣٢٪, has been reported by **Al-Zubaidy *et al.*** [(٥٠)].

Hence, the difference between the results of this study and that obtained by **Al-Zubaidy *et al.*** may be because they used a constant W/C ratio for all levels of replacement even at the total replacement of sand. Therefore, the mixes became very stiff and then a significant reduction in strength may have occurred due to the lack of compaction of the mixes.

It can be noticed also that the effect of replacing sand by CKD on the compressive strength is more pronounced in relatively lean mixes (series SRA) than in rich mixes (series SRB). See Figs.(٤-٥) and (٤-٦). For example, the ٧ days compressive strength of concrete containing ٢٠٪ of CKD (series SRA) exceeded that of the control concrete by about ٢٥.٥٪, while about ٥.٥٪ reduction in series SRB. Also, the ٧ days compressive strength of concrete containing ٥٠ % of CKD decreased by about ٣.٢٪ in series SRA, while about ٢٠.٨٪ in series SRB. This variation in strength is due to the presence of CKD which may fill the pores of lean concrete mixes. But for rich mixes, in which the cement paste as a fine material has filled most of the pores of concrete, CKD will not help in increasing the strength, but above a certain limit, will cause a reduction in strength. In addition, the fine materials can be beneficial for lean concretes probably because of its ability to modify the structure of the cement paste, but it has a little effect in concretes which are relatively rich in cement [٦, ٤٣].

The development of compressive strength of concrete with respect to ٢٨-day strength for series SRA and SRB is shown in Figs (٤-٩) and (٤-١٠). At ٧ days, it can be noticed that replacing ٢٠ and ٣٠ percent of sand by CKD in series SRA develops ٨٠ to ٨٦ percent of the ٢٨ days strength, compared to about ٦٨.٥ percent for the control mix. This trend is not evident in series SRB. However, Fig.(٤-٩) shows that most of the compressive strength is gained in ٧ days, while the ٩٠ days strength did not show a significant strength development rate as that of ٧ days.

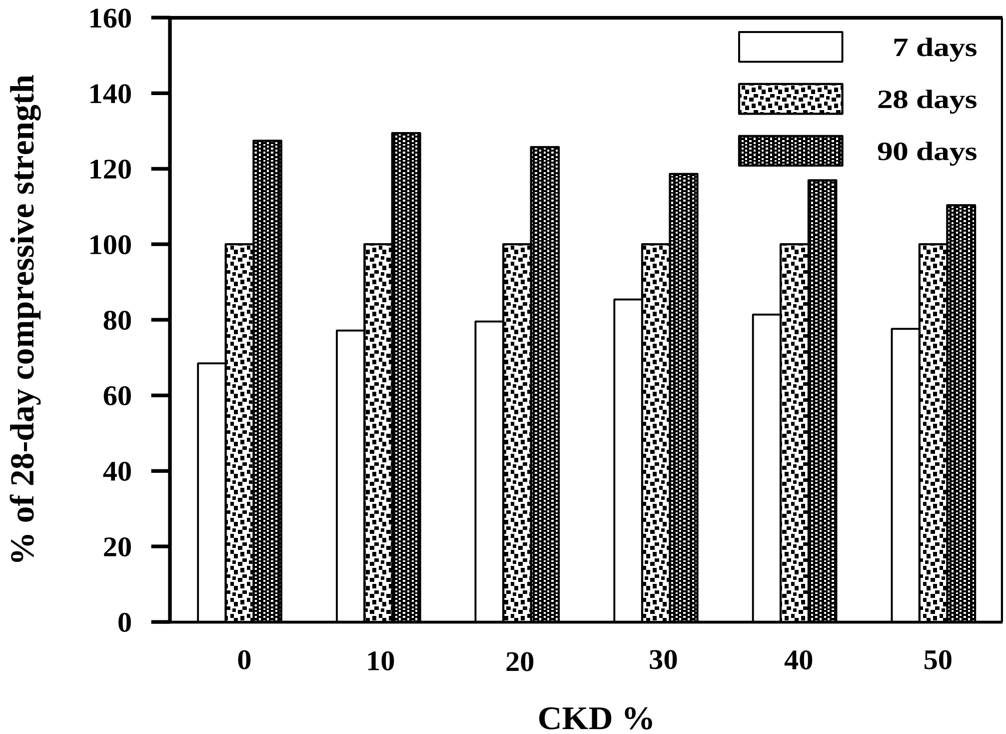

Fig.(٤-٩): Compressive strength development of concrete with respect to ٢٨-day strength for various percentages of sand replacement by CKD (series SRA).

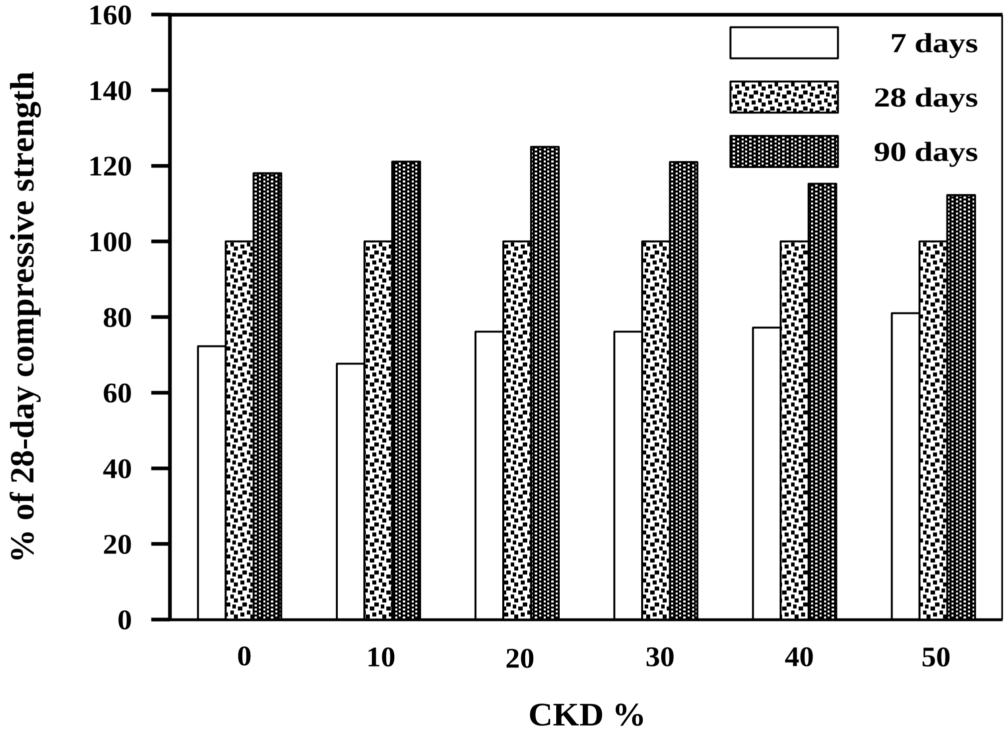

Fig.(٤-١٠): Compressive strength development of concrete with respect to ٢٨-day strength for various percentages of sand replacement by CKD (series SRB).

The contribution to the strength increase in ٧ days may be due to the presence of alkalies in CKD, which increases the rate of cement hydration at early ages [٧١]. Also, when the fine materials are used in the mix, the gain of concrete strength especially at early age can be attributed to the accelerated hydration of cement paste and to the filler effect of these materials [٤٢, ٧٢].

٤.٤.٢ Mortar Compressive Strength

The compressive strength of mortar for both cement and sand replacement by CKD at the ages of ٧, ٢٨ and ٩٠ days are discussed in the following sections.

٤.٤.٢.١ Effect of Cement Replacement by CKD on the Compressive Strength of Mortar

The results of the compressive strength up to an age of ٩٠ days for series CRL and CRM are presented in Table (٤-٥) and Figs.(٤-١١) and (٤-١٢).

Table (٤-٥): Influence of replacing cement and sand by CKD on the mortar compressive strength.

Mix Series		Specimen mark	Compressive strength (MPa)		
			٧ days	٢٨ days	٩٠ days
Replacing cement by CKD	CRL	CRL-٠	٢٧.٥٦	٣٥.١١	٤١.٧٨
		CRL-١٠	٢٤.٩٠	٣٣.٢٠	٣٩.٦٥
		CRL-٢٠	٢٣.٧٤	٣٠.٧٩	٣٨.٤٠
		CRL-٣٠	١٦.٨٩	٢١.٠٠	٣٥.٨١
		CRL-٤٠	١٢.٤٠	١٨.٧٥	٢٥.٥٧
	CRM	CRM-٠	٣٢.٩٠	٣٩.٦٠	٤٤.٧٩
		CRM-١٠	٣٠.٢٠	٣٨.٢٥	٤٠.٠٤
		CRM-٢٠	٢٧.٩٣	٣٦.٥٠	٣٩.٢٣
		CRM-٣٠	٢٦.٢٣	٣٢.٨٧	٣٤.٨٧
		CRM-٤٠	٢٠.٢٥	٢٩.٣٤	٢٩.٧٠
Replacing sand by CKD	SRL	SRL-٠	٢٧.٥٦	٣٥.١١	٤١.٧٨
		SRL-١٠	٣١.٢٤	٣٩.٤٣	٤٨.٠٩
		SRL-٢٠	٣١.٩٧	٣٧.٥٧	٤٦.٥٠
		SRL-٣٠	٢٩.٧٧	٣٢.٢٣	٣٦.٦٨
		SRL-٤٠	٢٥.٥٧	٢٨.١٠	٢٩.١٣
	SRM	SRM-٠	٣٢.٩٠	٣٩.٦٠	٤٤.٧٩
		SRM-١٠	٣٠.٩٣	٤٢.٠٠	٤٥.٦٠
		SRM-٢٠	٣٠.١٧	٤٠.٤٧	٤١.١٨
		SRM-٣٠	٢٨.٠٠	٣٥.٦٠	٣٧.٠٦
		SRM-٤٠	٢٢.٧٠	٢٨.٠٤	٢٧.٣٣

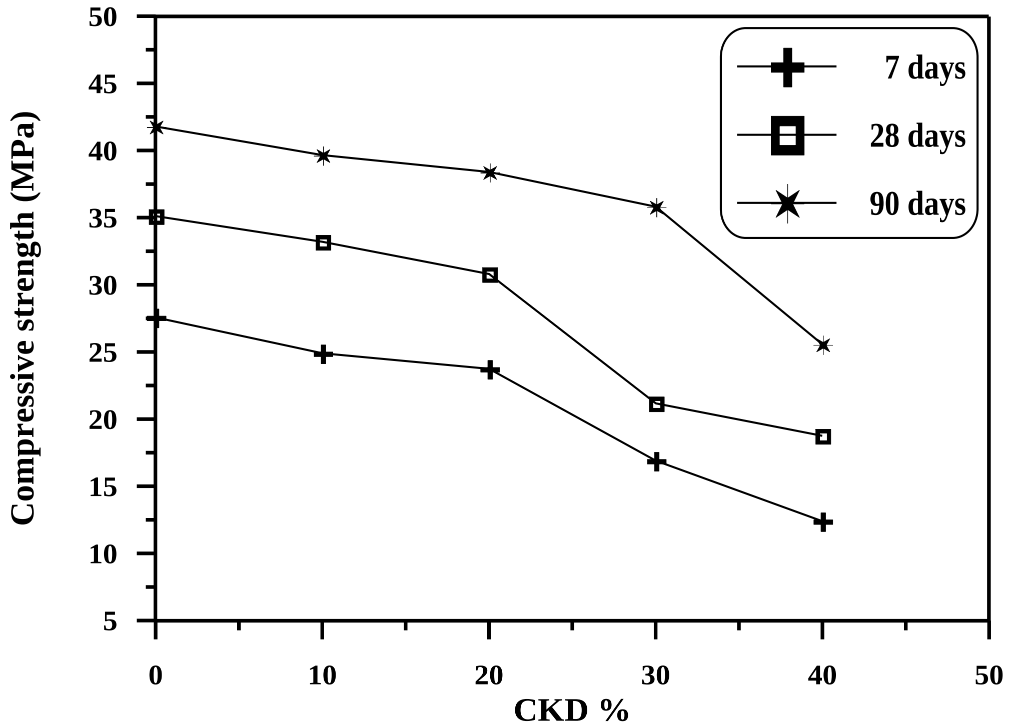

Fig.(٤-١١): Relationship between the compressive strength of mortar mixes (series CRL) and percentages of partial replacement of cement by CKD.

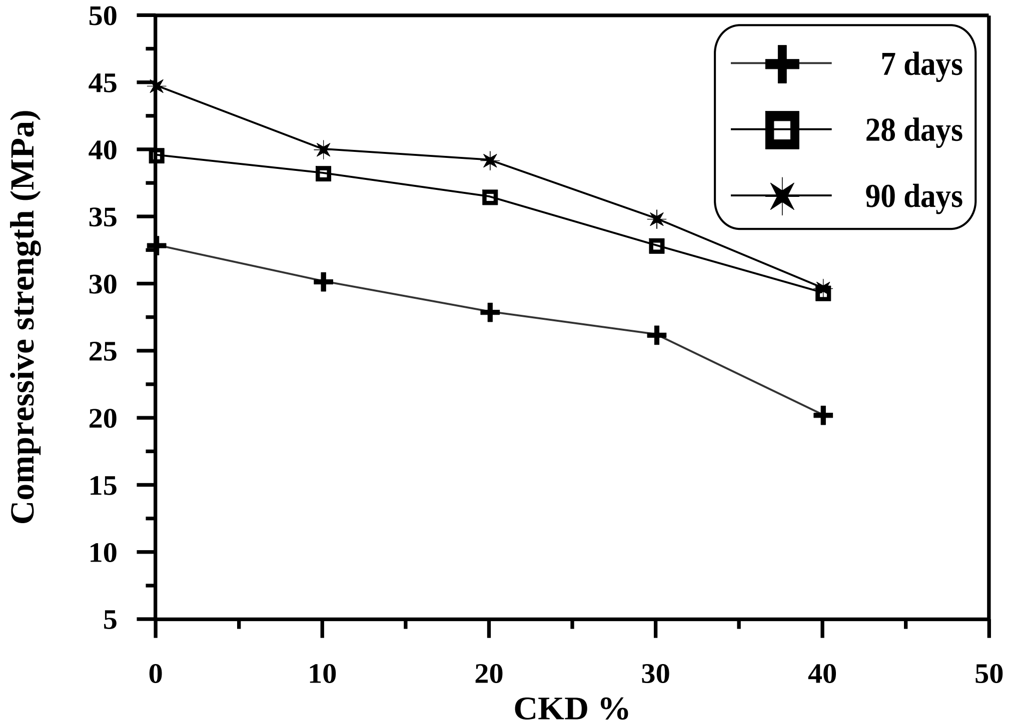

Fig.(٤-١٢): Relationship between the compressive strength of mortar mixes (series CRM) and percentages of partial replacement of cement by CKD.

The results have shown that the presence of CKD as cement replacement in mortar leads to reduce the compressive strength and this reduction is more pronounced when the cement replacement amount is increased. This may be attributed to the decrease in cement content of the mix and also due to the adverse effect of alkalies, sulphates and chlorides which are present in the dust. It may be noticed that there is no significant change in the compressive strength when up to ٢٠٪ of cement is replaced by CKD.

The results of compressive strength as a function of curing time are plotted in Figs.(٤-١٣) and (٤-١٤). It can be observed that the compressive strength develops with curing time for all hardened samples. This development may be due to the presence of cementitious materials in CKD composition which leads to the formation and accumulation of hydration products with age.

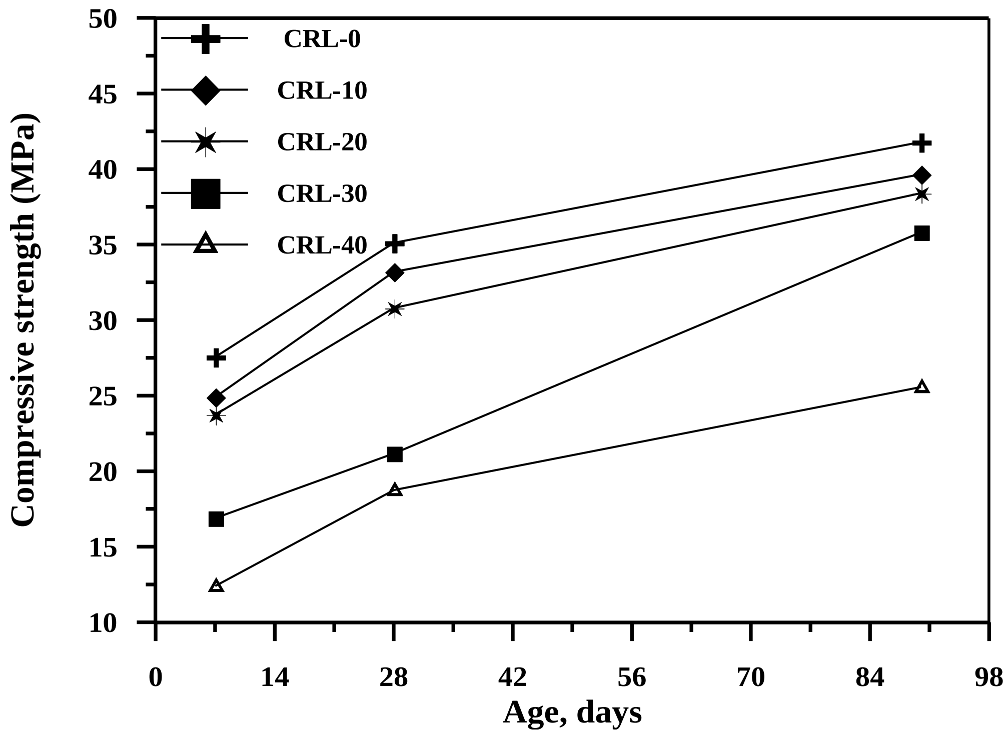

Fig.(٤-١٣): Development of compressive strength versus curing age for mortars containing varying proportions of CKD as percentage of cement (series CRL).

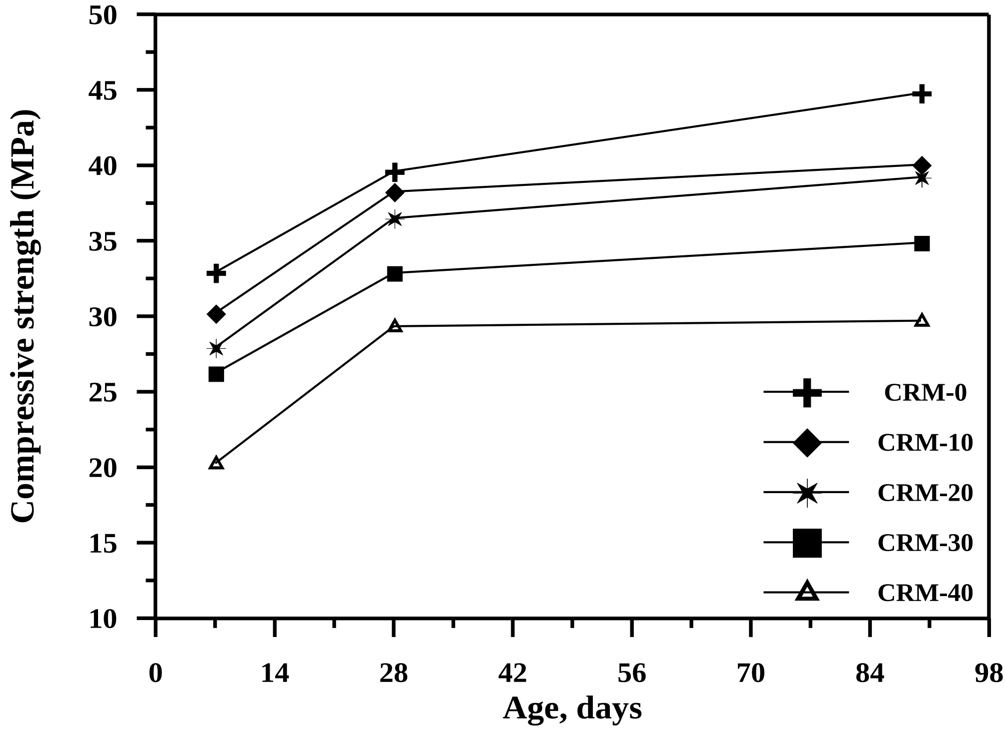

Fig.(٤-١٤): Development of compressive strength versus curing age for mortars containing varying proportions of CKD as percentage of cement (series CRM).

٤.٤.٢.٢ Effect of Sand Replacement by CKD on the Mortar Compressive Strength

The effect of CKD as partial replacement for sand on the mortar compressive strength has been studied using two series which are SRL and SRM. Details of the results are shown in Table (٤-٥) and Figs.(٤-١٥) and (٤-١٦).

Fig.(٤-١٥) shows that the presence of CKD in the mortar has shown an increase in compressive strength up to a certain percentage, and then the strength reduces as CKD percentage increases. The best strength has been achieved at ٧ days for series SRL which contains ٢٠٪ of CKD. The compressive strength at this level is ١٦٪ more than that of the control mix. At ٢٨ and ٩٠ days less enhancement in strength is observed.

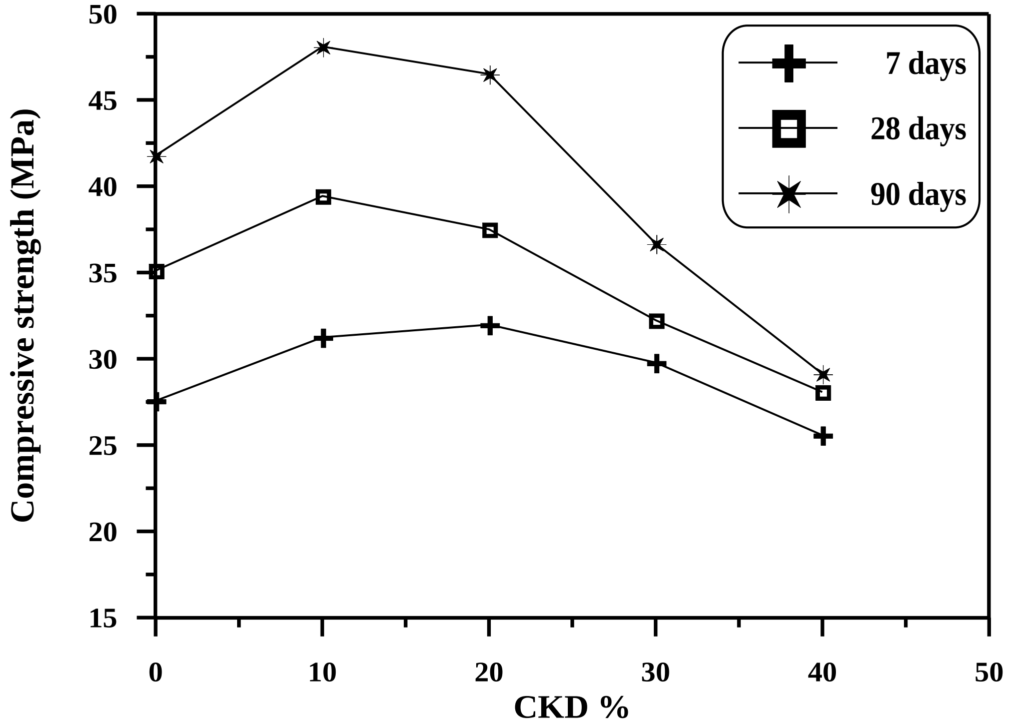

Fig.(٤-١٥): Influence of replacing sand by CKD on the compressive strength of mortar (series SRL).

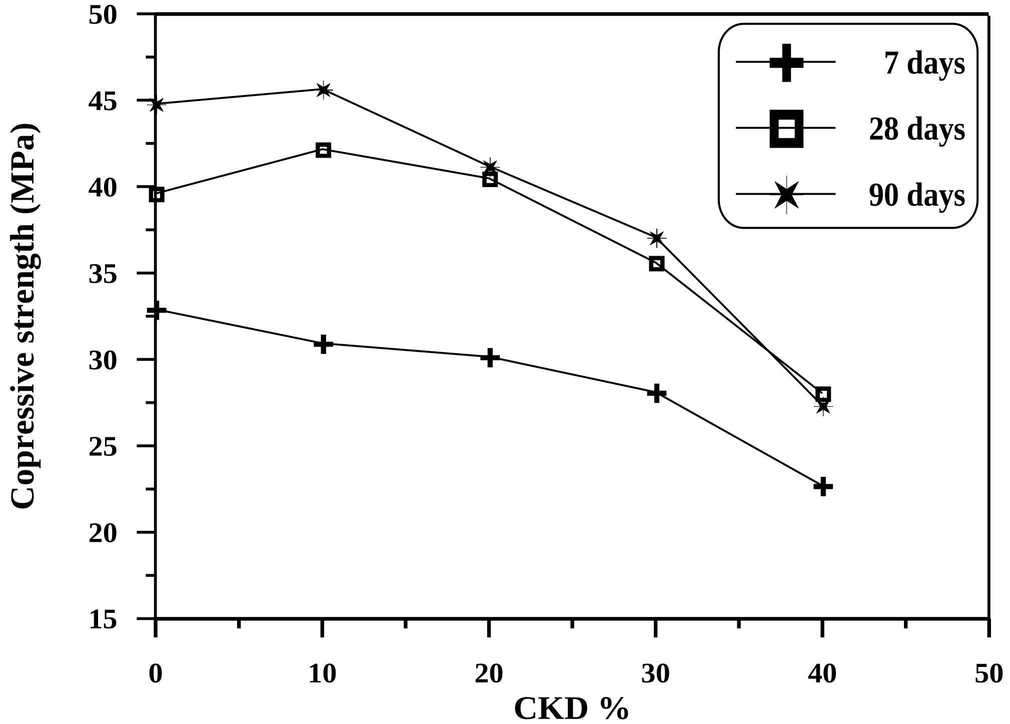

Fig.(٤-١٦): Influence of replacing sand by CKD on the compressive strength of mortar (series SRM).

For series SRM, the results of ٧ days strength have shown that the presence of CKD is slightly reducing the strength of mortar up to ١٠٪ of CKD replacement, while some enhancement in strengths are observed in ٢٨ and ٩٠ days. See Fig.(٤-١٦).

The compressive strength development with time up to ٩٠ days is shown in Figs.(٤-١٧) and (٤-١٨). It is clear from Fig.(٤-١٧) that the mortar specimens having CKD of ١٠, ٢٠ and ٣٠ percent have shown a compressive strength more than that of the control mix at ٧ days. In addition, the strength of specimens having up to ٢٠٪ of CKD is higher than that of the control mix at all ages.

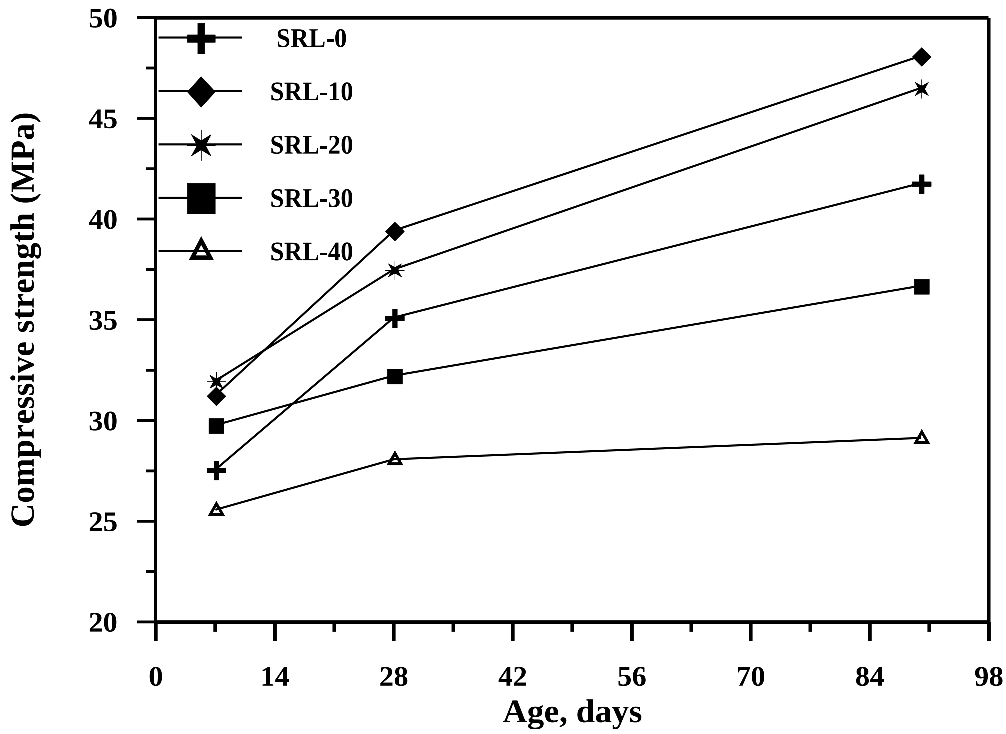

Fig.(٤-١٧): Development of compressive strength versus curing time for mortars containing varying proportions of CKD as percentage of sand (series SRL).

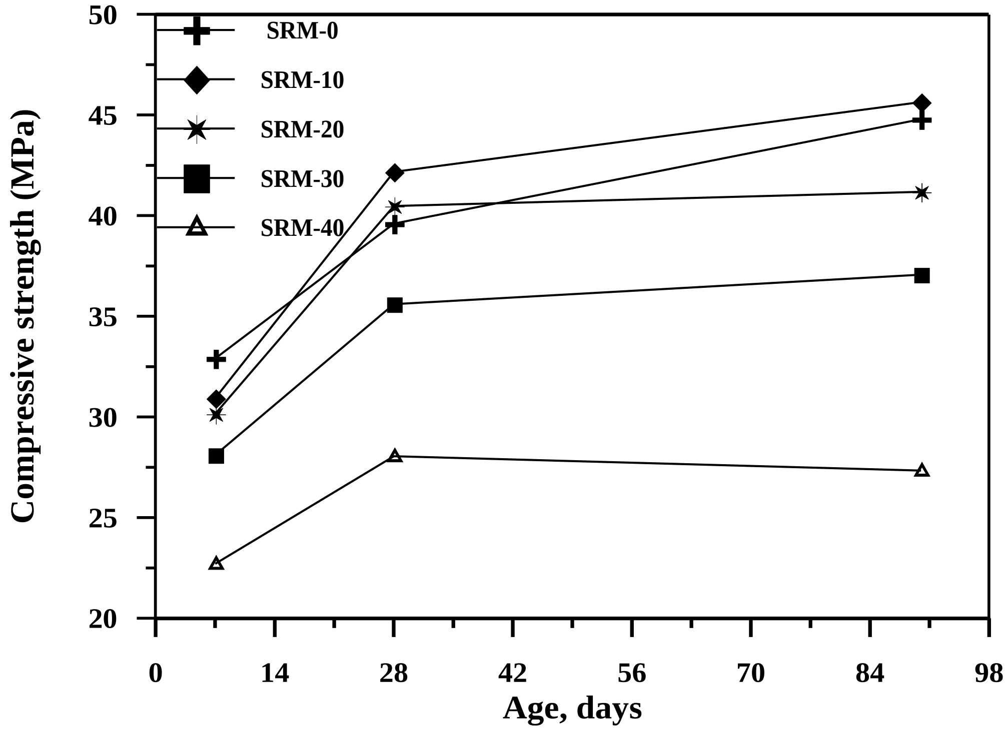

Fig.(٤-١٨): Development of compressive strength versus curing time for mortars containing varying proportions of CKD as percentage of sand (series SRM).

From Fig.(٤-١٨), generally, it can be observed that the compressive strength values increase with time, especially for a level of ١٠٪ of CKD. But, the mortar mix containing ٤٠٪ of CKD does not develop strength even after longer curing periods.

The development of compressive strength with respect to ٢٨-day strength is plotted in Figs.(٤-١٩) and (٤-٢٠). At ٧ days, it is found from Fig.(٤-١٩) that replacing ٢٠ and ٣٠ percent of sand by CKD develops ٨٥ to ٩٢ percent of the ٢٨-day strength, compared to about ٧٨ percent for the control mix. This means that most of compressive strength is gained in ٧ days. From Fig.(٤-٢٠), this gain in strength is not evident.

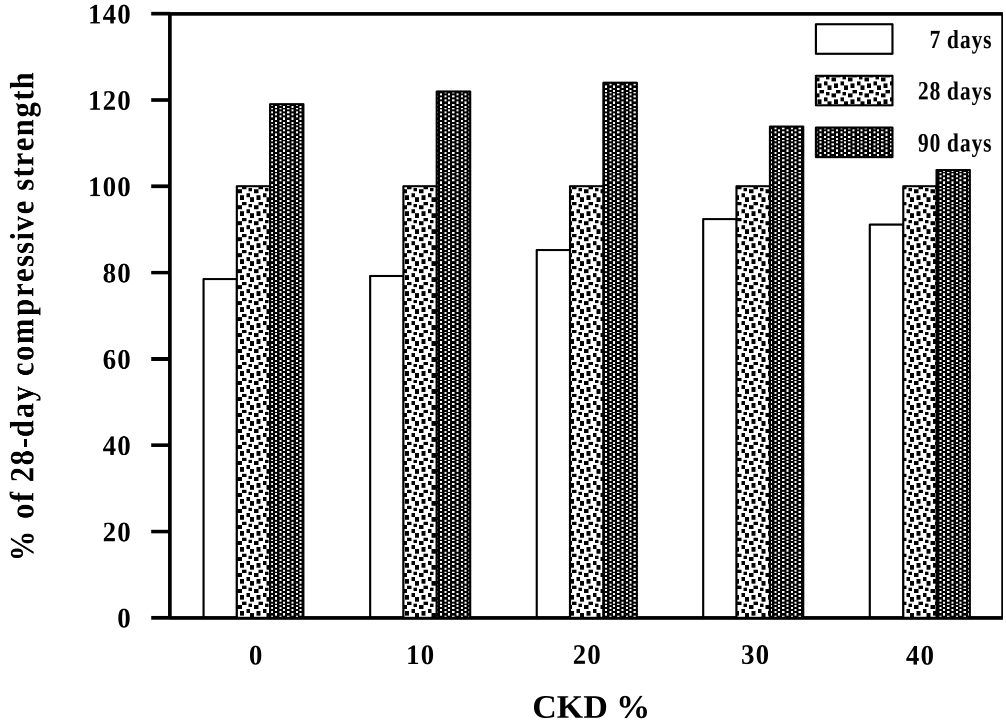

Fig.(٤-١٩): Compressive strength development of mortar with respect to ٢٨-day strength for various percentages of sand replacement by CKD (series SRL).

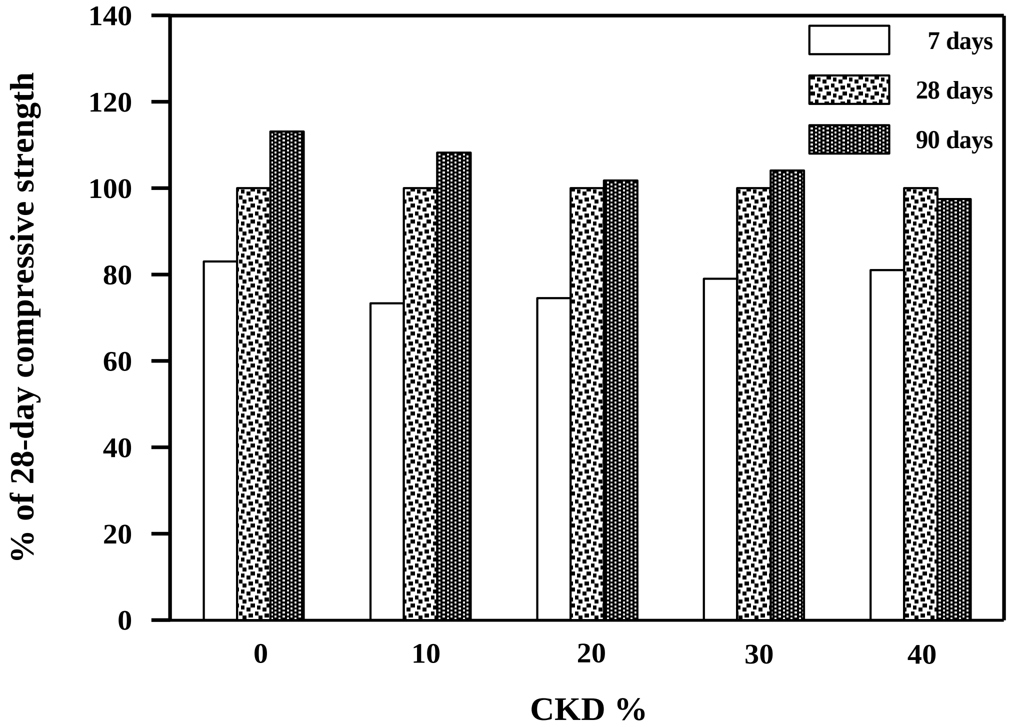

Fig.(٤-٢٠): Compressive strength development of mortar with respect to ٢٨-day strength for various percentages of sand replacement by CKD (series SRM).

٤.٥ Modulus of Rupture Test Resutls

The modulus of rupture of concrete was determined after ٢٨ and ٩٠ days of moist curing. The results of all mixes are presented in Table (٤-٦).

Table (٤-٦): Modulus of rupture of concrete when CKD is used as partial cement and sand replacement.

Mix Series		Specimen mark	Modulus of rupture (MPa)	
			٢٨ days	٩٠ days
Replacing cement by CKD	CRA	CRA-٠	٣.٤٣	٤.٢٧
		CRA-١٠	٣.١٠	٤.١٢
		CRA-٢٠	٣.٠٢	٣.٧٢
		CRA-٣٠	٢.٤٦	٢.٧٤
		CRA-٤٠	٢.٠٤	٢.٥٧
		CRA-٥٠	١.٧٤	٢.٠٣
	CRB	CRB-٠	٣.٩١	٤.٧٣
		CRB-١٠	٣.٥٠	٤.٥٤
		CRB-٢٠	٣.١٣	٣.٩٠
		CRB-٣٠	٢.٥٤	٢.٩٦
		CRB-٤٠	٢.٤٨	٢.٧٦
		CRB-٥٠	١.٩٥	٢.٤٠
Replacing sand by CKD	SRA	SRA-٠	٣.٤٣	٤.٢٧
		SRA-١٠	٣.٦٣	٤.٦٢
		SRA-٢٠	٣.٧٠	٤.٥٠
		SRA-٣٠	٣.١٢	٣.٩٦
		SRA-٤٠	٢.٨٥	٣.١٠
		SRA-٥٠	٢.٦٩	٢.٧٧
	SRB	SRB-٠	٣.٩١	٤.٧٣
		SRB-١٠	٣.٦٠	٤.٥٣
		SRB-٢٠	٣.٥٣	٤.١٣
		SRB-٣٠	٢.٩٦	٣.٨٠
		SRB-٤٠	٢.٧٢	٣.٠٧
		SRB-٥٠	٢.٦٠	٢.٥١

The effect of CKD on the modulus of rupture is found to be somewhat similar to that of compressive strength. For mixes with cement partially replaced by CKD (series CRA and CRB), Figs.(٤-٢١) and (٤-٢٢) show that the modulus of rupture of concrete decreases with the increase of CKD content, especially with a high value of substitution. Up to ١٠٪, this decrease is slightly lower than that of the control mix. However, the modulus of rupture decreases rapidly, especially at ٩٠ days, when more than ٢٠٪ of CKD as cement replacement is added. For example, the ٩٠ days modulus of rupture in series CRA decreased from ١٣ to ٣٥ percent when the partial replacement ratio was increased from ٢٠ to ٣٠ percent.

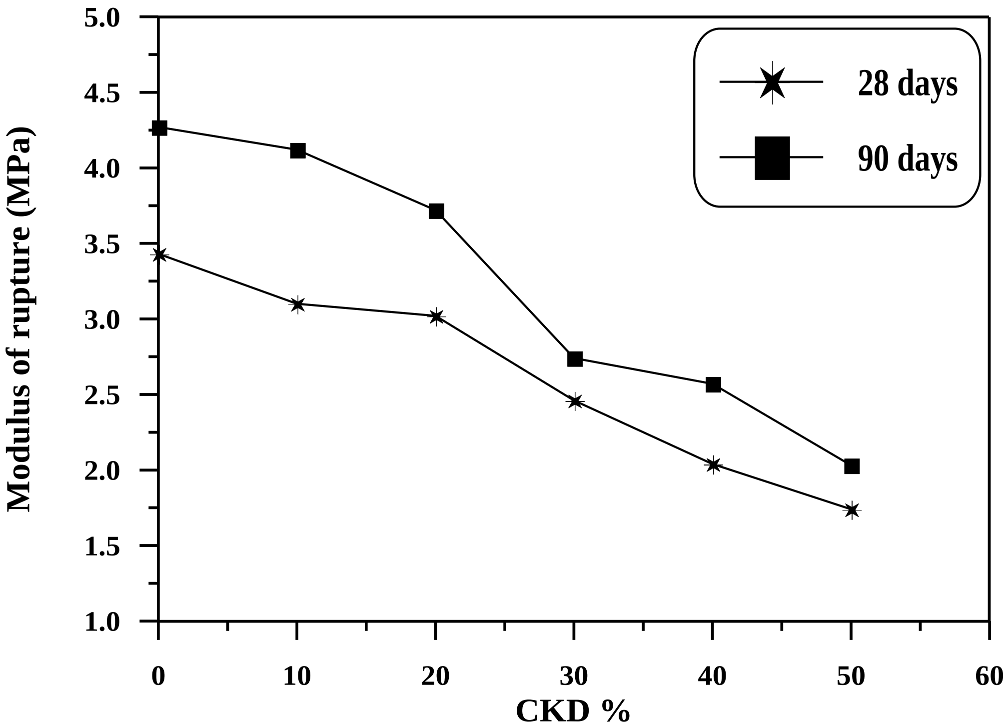

Fig.(٤-٢١): Influence of replacing cement by CKD on the modulus of rupture of concrete (series CRA).

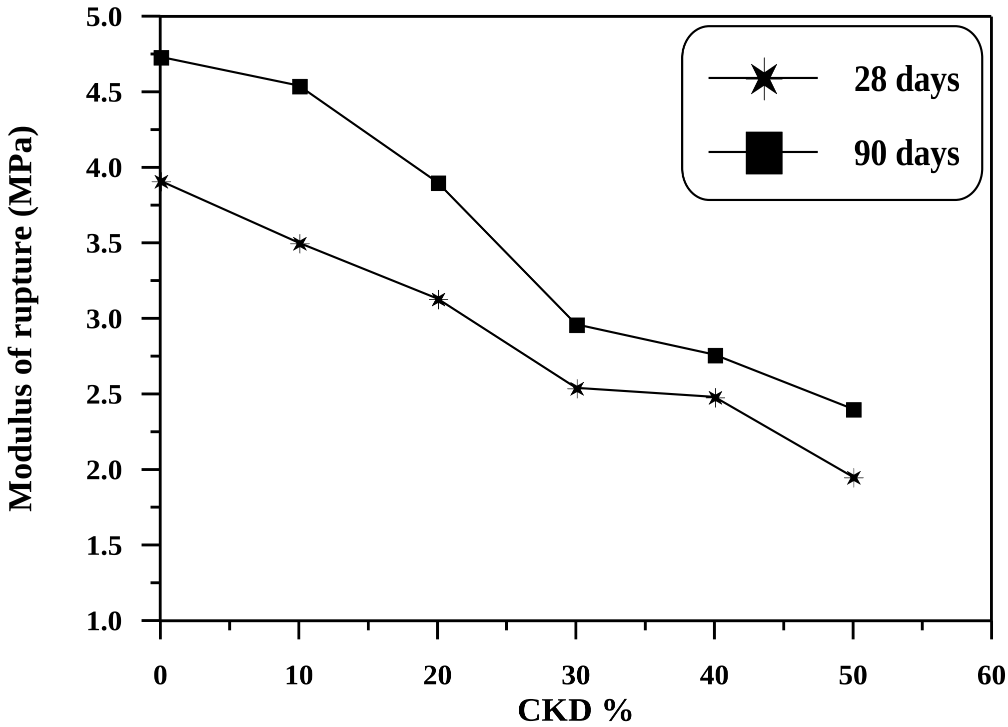

Fig.(٤-٢٢): Influence of replacing cement by CKD on the modulus of rupture of concrete (series CRB).

The effect of partial replacing sand by CKD on the modulus of rupture in both series SRA and SRB is shown in Figs.(٤-٢٣) and (٤-٢٤). As with compressive strength, it is found that replacing sand by CKD gives variable effect on the modulus of rupture according to the richness of the mix. For series SRA, Fig.(٤-٢٣) shows that the addition of CKD improves the modulus of rupture up to ٢٠٪, whereas the presence of CKD has reduced the modulus of rupture in series SRB. See Fig.(٤-٢٤).

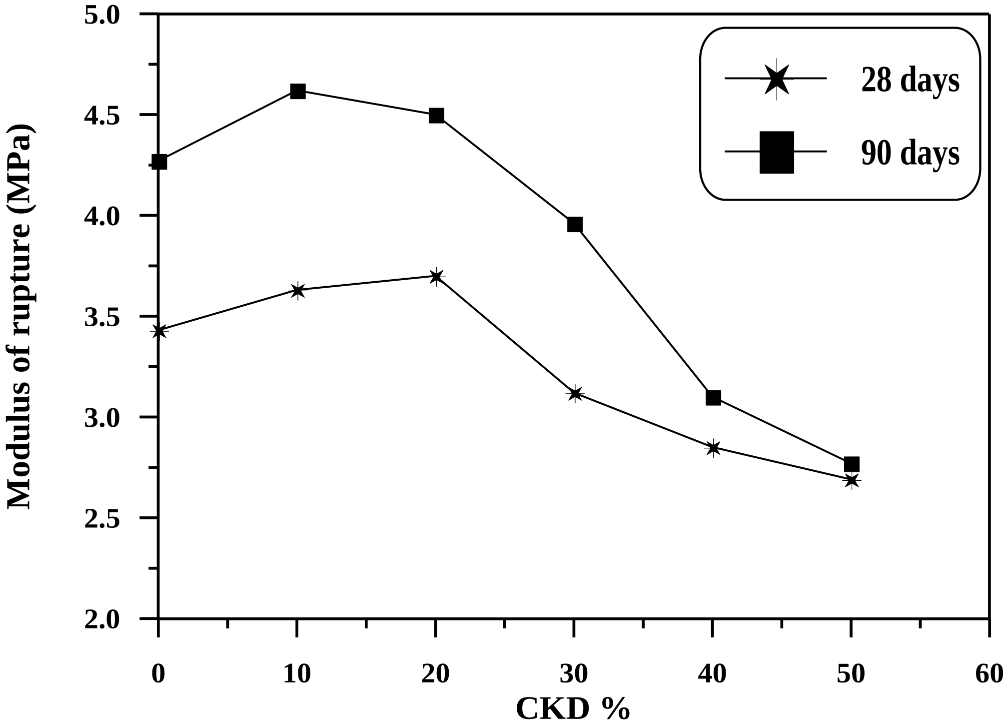

Fig.(٤-٢٣): Relationship between the modulus of rupture of concrete (series SRA) and the percentages of partial replacement of sand by CKD.

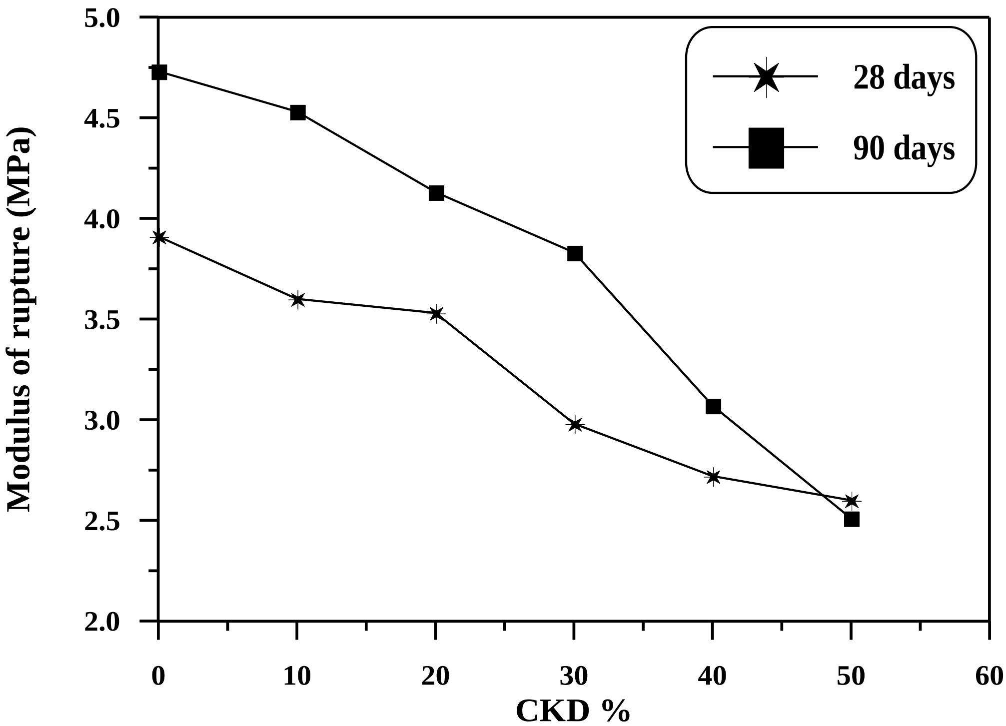

Fig.(٤-٢٤): Relationship between the modulus of rupture of concrete (series SRB) and the percentages of partial replacement of sand by CKD.

٤.٦ Splitting Tensile Strength Test Results

The influence of replacing cement and sand partially by CKD on the splitting tensile strength is presented in Table (٤-٧). The splitting tensile strength results show trends similar to that observed in the modulus of rupture of the corresponding concretes. It is found, from Figs.(٤-٢٥) and (٤-٢٦) that replacement of cement by CKD reduces the splitting tensile strength of concrete. This reduction is more pronounced at larger contents of CKD.

Table (٤-٧): Effect of replacing cement and sand by CKD on the splitting tensile strength of concrete.

Mix Series		Specimen mark	Splitting tensile strength (MPa)	
			٢٨ days	٩٠ days
Replacing cement by CKD	CRA	CRA-٠	٢.٦٠	٣.١١
		CRA-١٠	٢.٤٥	٢.٨٥
		CRA-٢٠	٢.١٠	٢.٧٢
		CRA-٣٠	١.٨٠	٢.٢٣
		CRA-٤٠	١.٥٢	١.٧٠
		CRA-٥٠	١.٢٦	١.٣٢
	CRB	CRB-٠	٢.٨٨	٣.٣٧
		CRB-١٠	٢.٧٧	٣.٣٠
		CRB-٢٠	٢.٤٥	٢.٨٦
		CRB-٣٠	٢.١٨	٢.٧٣
		CRB-٤٠	١.٦٥	١.٨٠
		CRB-٥٠	١.٥٠	١.٧١
Replacing sand by CKD	SRA	SRA-٠	٢.٦٠	٣.١١
		SRA-١٠	٢.٦٣	٣.١٧
		SRA-٢٠	٢.٨٨	٣.٢٢
		SRA-٣٠	٢.٤٠	٢.٧٤
		SRA-٤٠	٢.٢٦	٢.٣٣
		SRA-٥٠	٢.٠٠	٢.١٥
	SRB	SRB-٠	٢.٨٨	٣.٣٧
		SRB-١٠	٢.٦٧	٣.٣٥
		SRB-٢٠	٢.٥٨	٣.١٤
		SRB-٣٠	٢.٣٠	٢.٦٣
		SRB-٤٠	٢.١٥	٢.٣٠
		SRB-٥٠	١.٨٠	١.٨٥

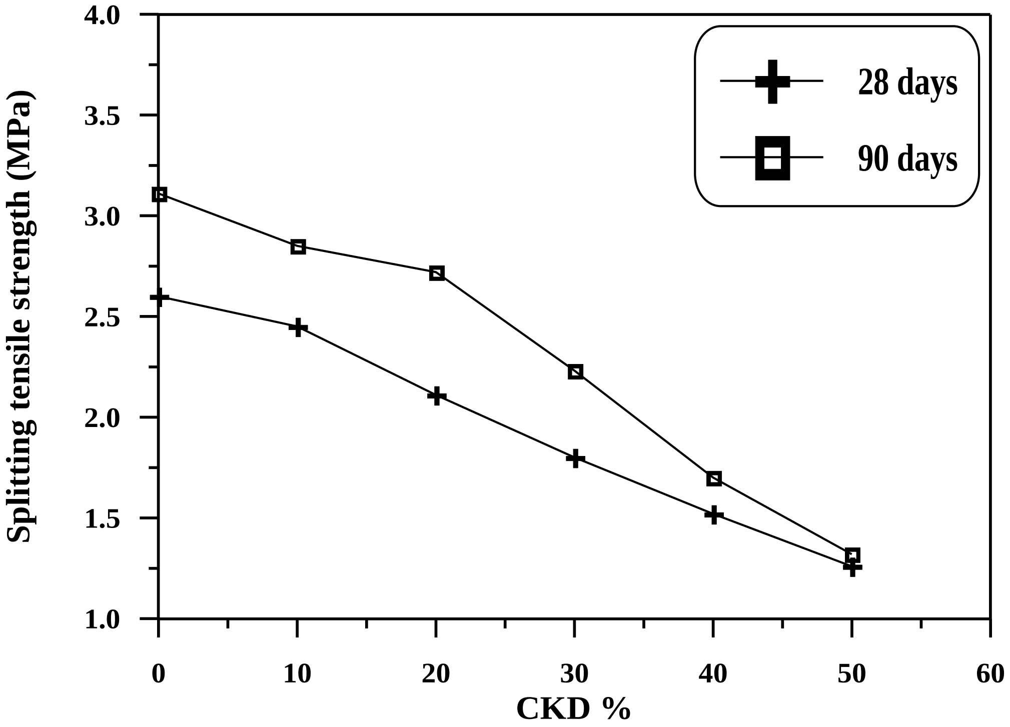

Fig.(٤-٢٥): Influence of cement replacement by CKD on the splitting tensile strength of concrete (series CRA).

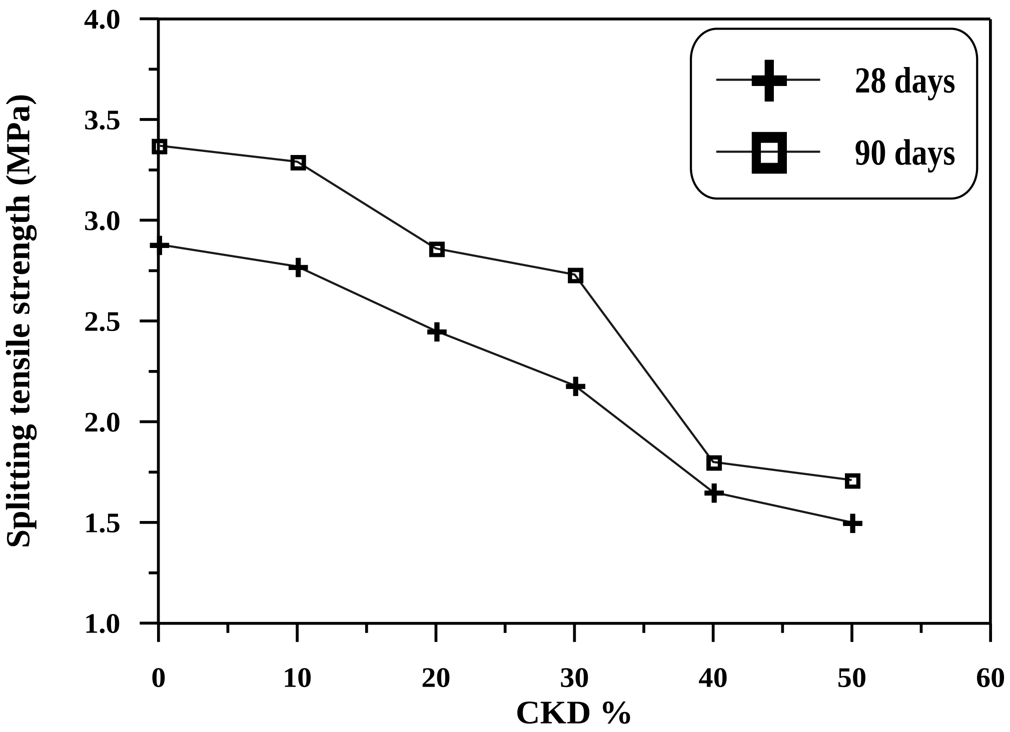

Fig.(٤-٢٦): Influence of cement replacement by CKD on the splitting tensile strength of concrete (series CRB).

From Fig.(٤-٢٧), it has been found that the splitting tensile strength is improved when ١٠ and ٢٠ percent of sand are replaced by CKD. Fig.(٤-٢٨) indicates that the splitting tensile strength decreases with the addition of CKD. This decrease depends on the percentage of sand that is replaced by CKD.

It can be stated that, at high levels of both cement and sand replacement, the decrease is more pronounced in the tensile strength than in compressive strength of the corresponding concrete, especially at the age of ٩٠ days. Generally, from a previous study, similar results are reported by **Shoaib *et al*.** (٤٩). They noticed that the use of large percentages of CKD show a gradual decrease in the splitting tensile strength of concrete samples. Also, they reported that this decrease can be attributed to the increasing CKD content which does not offer good bond between aggregate and cement paste.

It is reported that, as significant percentages of alkalies in the mix are present, the structure of cement paste becomes hetrogeneous and a reduction in strength will result (٧١). Since the bond between aggregate and cement is affected by the chemical and structural composition of cement paste (٧٣); therefore, the presence of large amounts of CKD which is rich in alkalies content, furtherly reduces tensile strength as well as compressive strength through the reduction in bond strength.

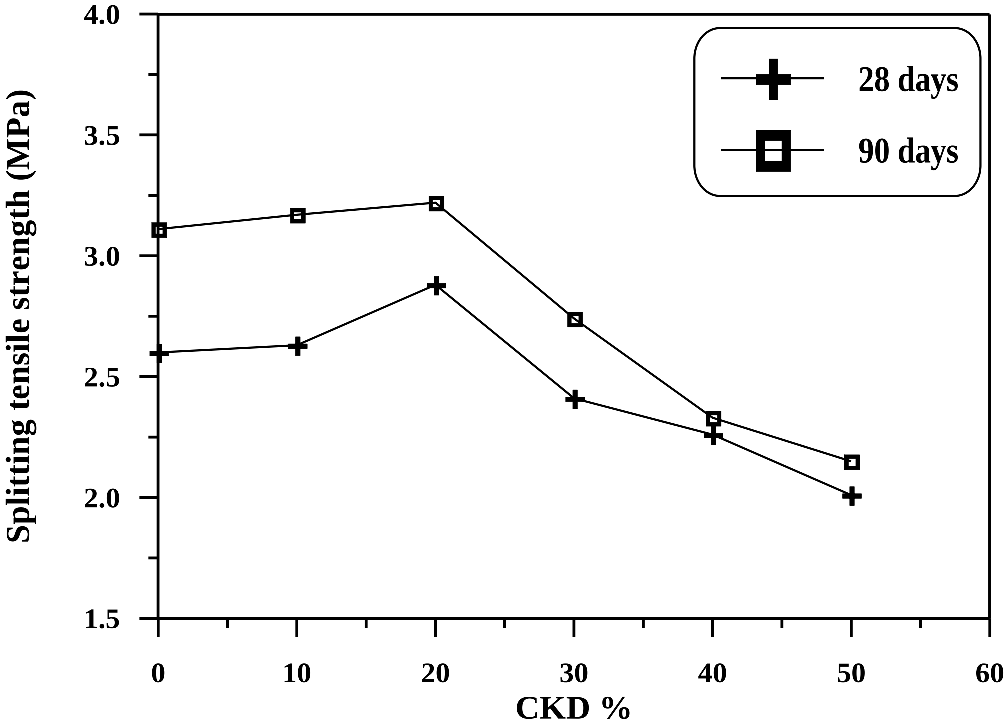

Fig.(٤-٢٧): Influence of sand replacement by CKD on the splitting tensile strength of concrete (series SRA).

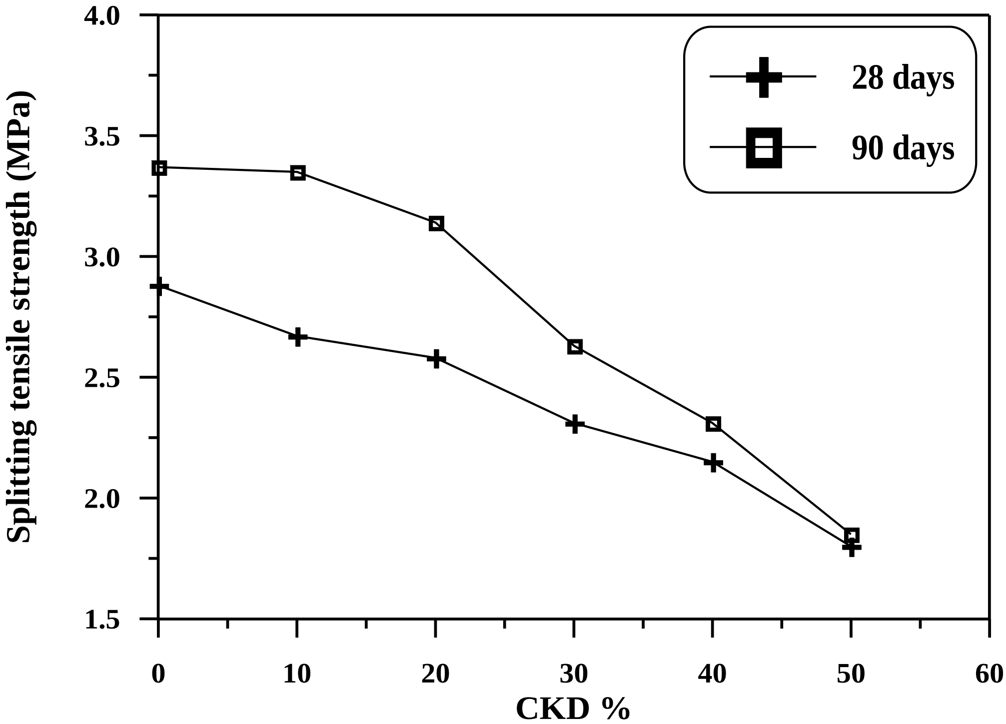

Fig.(٤-٢٨): Influence of sand replacement by CKD on the splitting tensile strength of concrete (series SRB).

٤.٧ Density Test Results

The ٢٨ days concrete density for both cement and sand replacement are presented in Figs.(٤-٢٩) and (٤-٣٠). Except for ١٠ and ٢٠ percent of sand replacement, the results show that the density of mixes decreases with the increase in the percentage of CKD. The reason of this decrease is that CKD has relatively lower specific gravity. Therefore, replacement of CKD, especially on the basis of weight, will decrease the density of the mixes when compared with the control mix. It can be observed also that in rich mixes (series CRB and SRB) when above ٣٠٪ of CKD is used, the reduction in the density is lower than that in relatively lean mixes (series CRA and SRA).

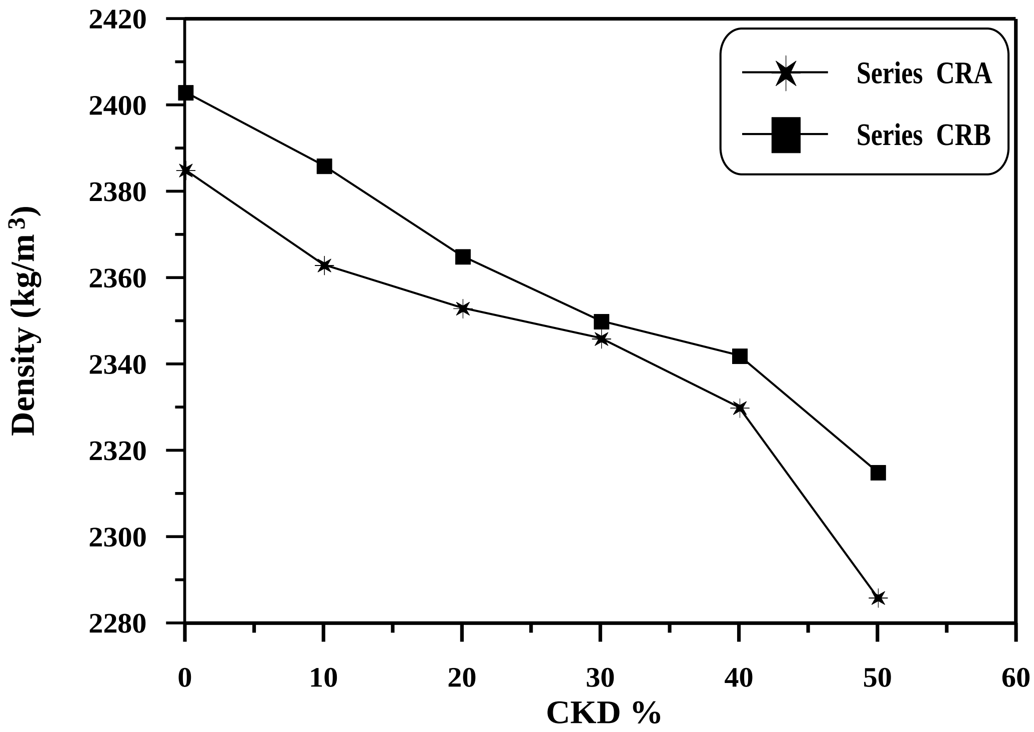

Fig.(٤-٢٩): Effect of replacing cement by CKD on the ٢٨ days concrete density.

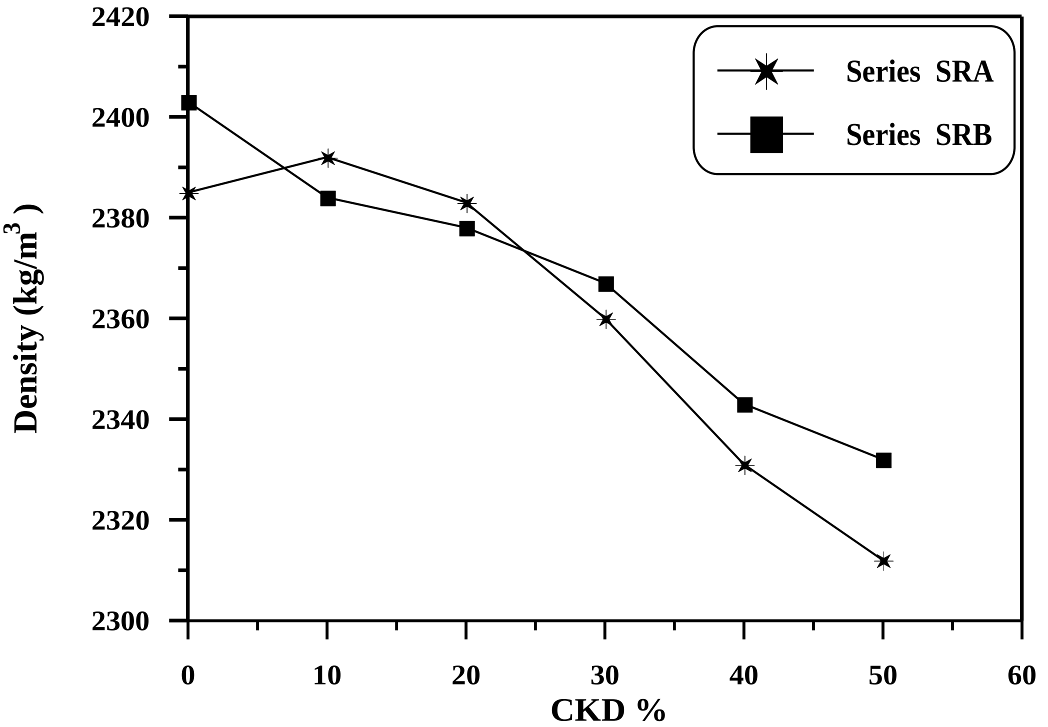

Fig.(٤-٣٠): Effect of replacing sand by CKD on the ٢٨ days concrete density.

Figs.(٤-٣١) and (٤-٣٢) present the relationship between the compressive strength of concrete samples and the density at ٢٨ days for all series. An empirical formula for this relationship can be developed as follows:

For series CRA and CRB:

$$F_{cu} = 7.619 \times 10^{-7} e^{0.0073\rho} \qquad \text{...........(٤.١)}$$

For series SRA and SRB:

$$F_{cu} = 0.0072 e^{0.0035\rho} \qquad \text{...........(٤.٢)}$$

where:

F_{cu} = compressive strength of ١٥٠ mm concrete cube, MPa.
ρ = concrete density, kg/m٣.

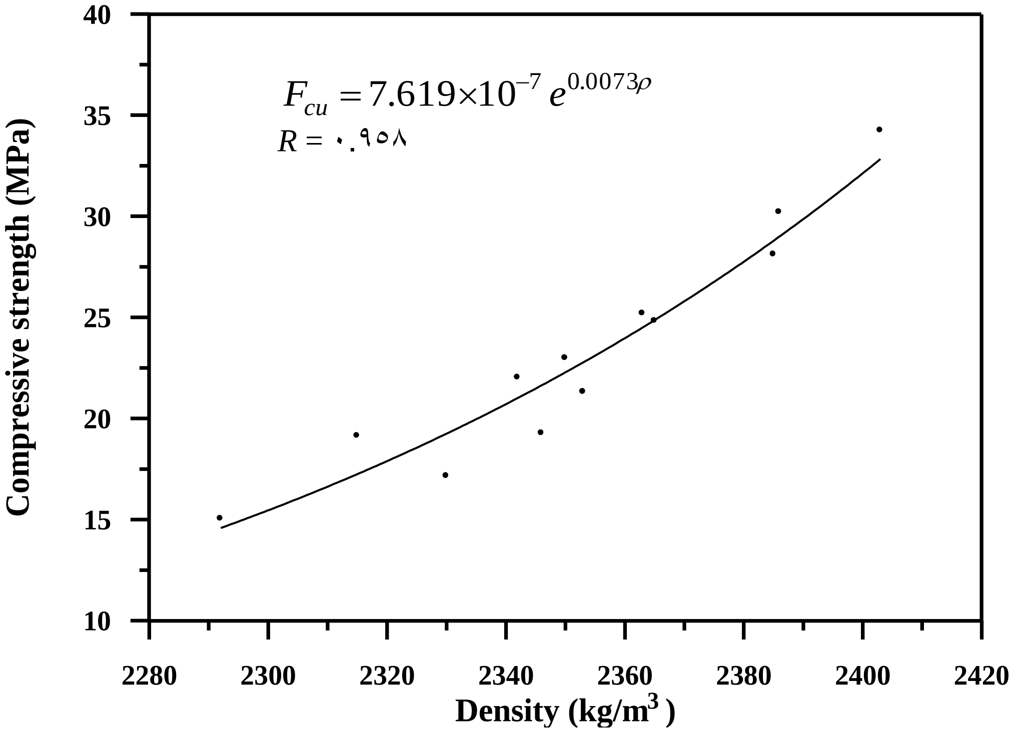

Fig.(٤-٣١): Relationship between the compressive strength of concrete and the density at ٢٨ days for various percentages of CKD as cement replacement.

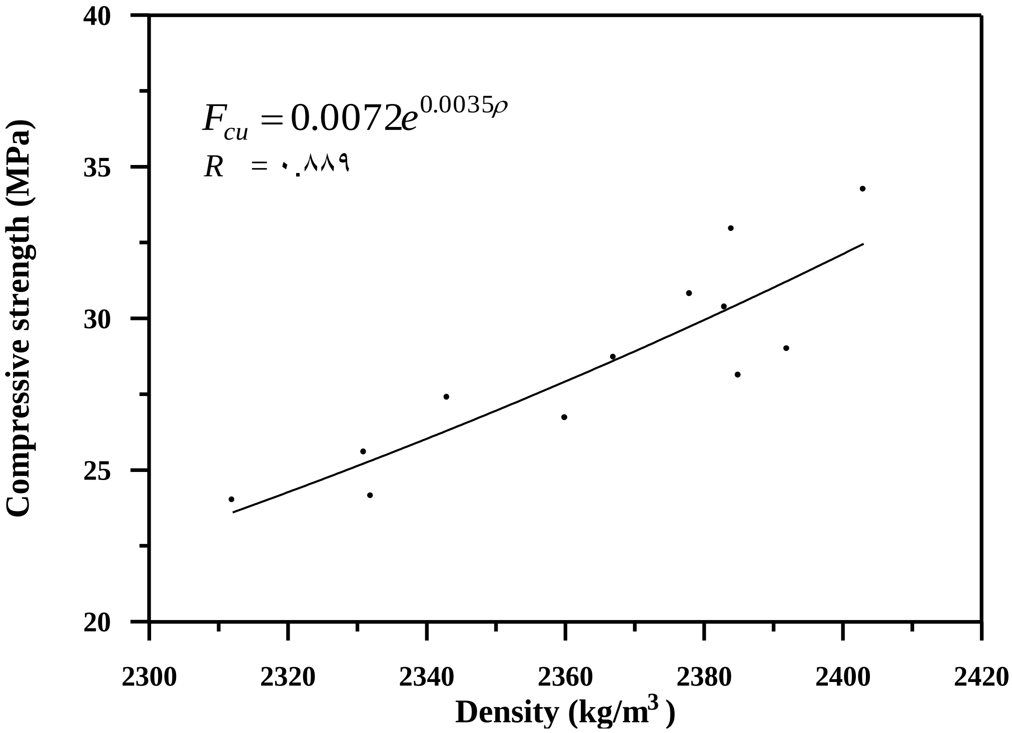

Fig.(٤-٣٢): Relationship between the compressive strength of concrete and the density at ٢٨ days for various percentages of CKD as sand replacement.

٤.٨ Ultrasonic Pulse Velocity Test Results

The ultrasonic pulse velocity of the concrete specimens was determined before finding the compressive strength by the destructive method. This test is a particularly suitable way to measure the quality of a concrete structure [٧٤]. The measured pulse velocity of concrete can be affected by many factors, including smoothness of concrete surface, temperature of concrete, moisture conditions, age of the specimen and presence of reinforcement [٧٥,٧٦]. Generally, high pulse velocity readings are indications of good quality concrete. The ranges of pulse velocity of different concrete qualities are shown in Table (٤-٨).

Table (٤-٨): Pulse velocity ranges for concrete [٧٧].

Pulse velocity (km/sec.)	Concrete quality
Above ٤.٥٨	Excellent
٣.٦٦ - ٤.٥٨	Good
٣.٠٥ - ٣.٦٦	Questionable
٢.١٤ - ٣.٠٥	Poor
Below ٢.١٤	Very poor

In this study,the values of pulse velocity with the addition of CKD as cement and sand replacement are shown in Table (٤-٩). Generally, it is found that the presence of CKD as cement replacement in the concrete mixes (series CRA and CRB) gives a reduction in the pulse velocity. See Figs.(٤-٣٣) and (٤-٣٤). This reduction in pulse velocity reflects the decrease in compressive and tensile strengths as well as the density of the mixes. It is also noticed that the concrete containing up to ١٠٪ of CKD as cement replacement shows a slight decrease in the pulse velocity.

The effect of replacing sand by CKD on the pulse velocity is shown in Figs.(٤-٣٥) and (٤-٣٦). It can be noticed from Fig.(٤-٣٥) that the presence of up to ٢٠ % of CKD in series SRA as sand replacement gives an increase in the ultrasonic pulse velocity of the concrete specimens which were tested at the age of ٧ days. This increase in pulse velocity is an indication to the ability of CKD to accelerate the hydration of cement paste at early ages.

In general, it is found from Fig.(٤-٣٦) that the presence of CKD as sand replacement in series SRB gives losses in pulse velocity. This means that richness of the mix yields differences in the effect of CKD on the ultrasonic pulse velocity.

Table (٤-٩): Ultrasonic pulse velocity of concrete with additions of CKD as partial replacement of cement and sand.

Mix Series		Specimen mark	Ultrasonic pulse velocity (km/sec)		
			٧ days	٢٨ days	٩٠ days
Replacing cement by CKD	CRA	CRA-٠	٤.٣٨٣	٤.٦٤٠	٤.٧٦٧
		CRA-١٠	٤.٢١١	٤.٤٣٢	٤.٧٨٠
		CRA-٢٠	٤.١٩٢	٤.٣٦٠	٤.٥٨١
		CRA-٣٠	٤.٠٨٠	٤.١٤٠	٤.٣٢٠
		CRA-٤٠	٣.٨٣٠	٣.٩٥٠	٤.٣٦٠
		CRA-٥٠	٣.٧٨٠	٣.٨٦٠	٤.١٥٠
	CRB	CRB-٠	٤.٥١٦	٤.٧٤٨	٤.٨٢٠
		CRB-١٠	٤.٣٥٢	٤.٤٧٠	٤.٧٨٠
		CRB-٢٠	٤.٣٧٢	٤.٤١٠	٤.٥٨١
		CRB-٣٠	٤.٢١٥	٤.٣٦١	٤.٤٥٠
		CRB-٤٠	٤.١٠٠	٤.١٥٠	٤.٤١١
		CRB-٥٠	٣.٨٨٠	٤.١٠٠	٤.١٨٠
Replacing sand by CKD	SRA	SRA-٠	٤.٣٨٣	٤.٦٤٠	٤.٧٦٧
		SRA-١٠	٤.٥٨٠	٤.٦٥١	٤.٨١٠
		SRA-٢٠	٤.٦٠٠	٤.٧٣٠	٤.٧٧٠
		SRA-٣٠	٤.٣٦٠	٤.٥٤٣	٤.٦٤٠
		SRA-٤٠	٤.٢٤٠	٤.٤٦٠	٤.٥٣١
		SRA-٥٠	٤.٢١٦	٤.٢٨٧	٤.٤١٠
	SRB	SRB-٠	٤.٥١٦	٤.٧٤٨	٤.٨٢٠
		SRB-١٠	٤.٥٢٠	٤.٧٢٦	٤.٨٦١
		SRB-٢٠	٤.٤٨٠	٤.٦٧٠	٤.٧٤٠
		SRB-٣٠	٤.٤٥٠	٤.٥١٠	٤.٦٩٠
		SRB-٤٠	٤.٢٩٢	٤.٤٥١	٤.٥٦٠
		SRB-٥٠	٤.٣٠٨	٤.٤١٠	٤.٤٣٧

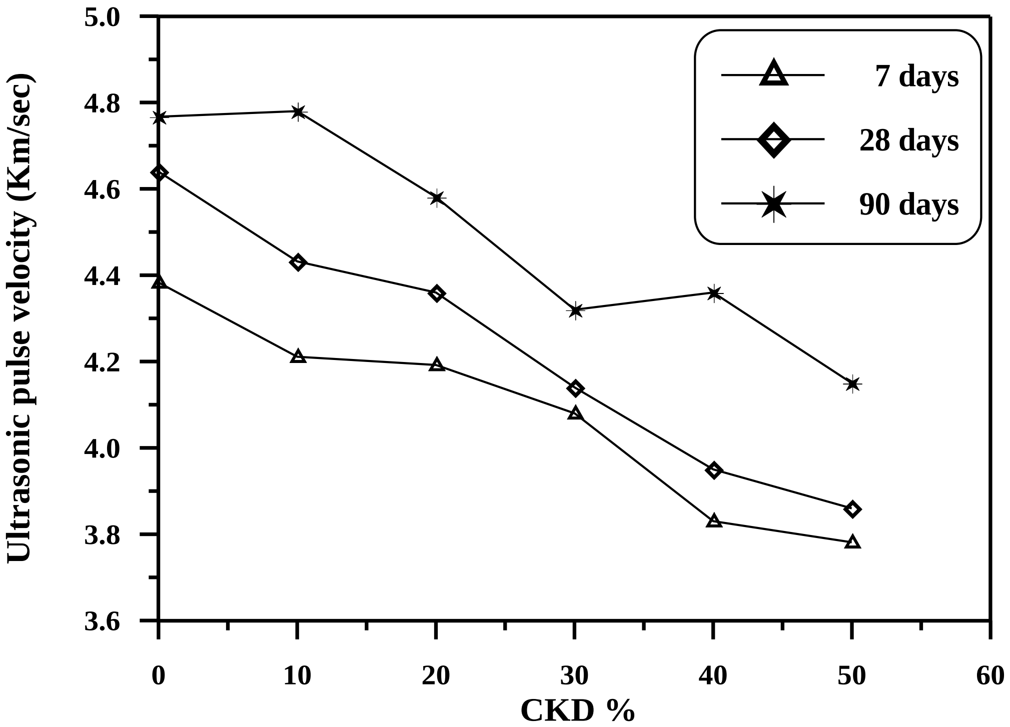

Fig.(٤-٣٣): Ultrasonic pulse velocity of concrete versus additions of different percentages of CKD as cement replacement (series CRA).

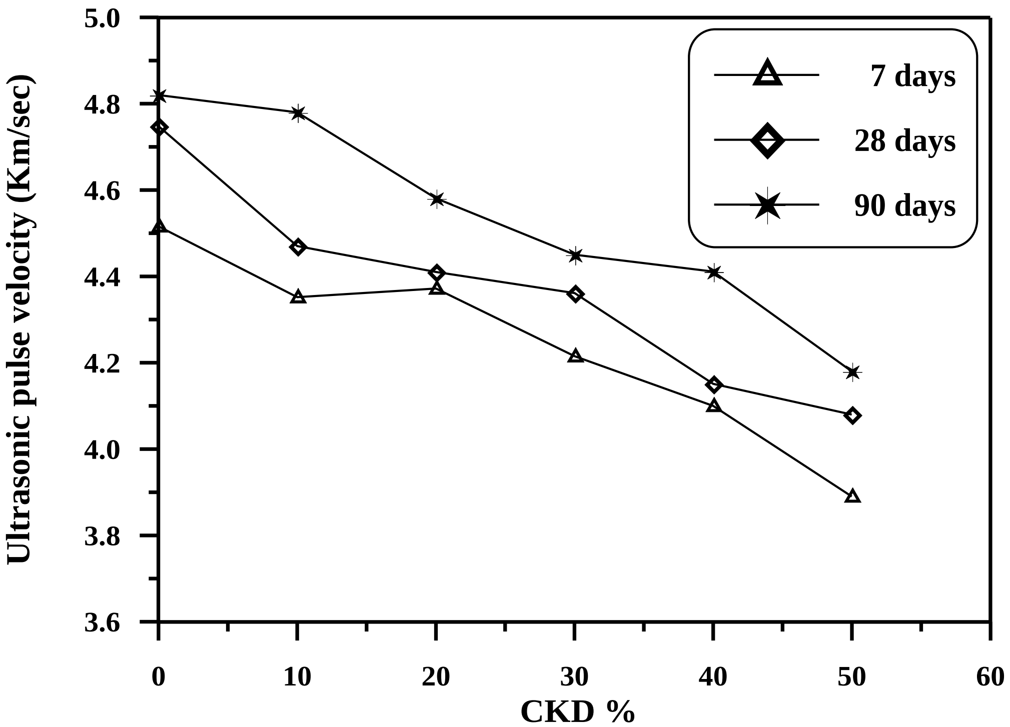

Fig.(٤-٣٤): Ultrasonic pulse velocity of concrete versus additions of different percentages of CKD as cement replacement (series CRB).

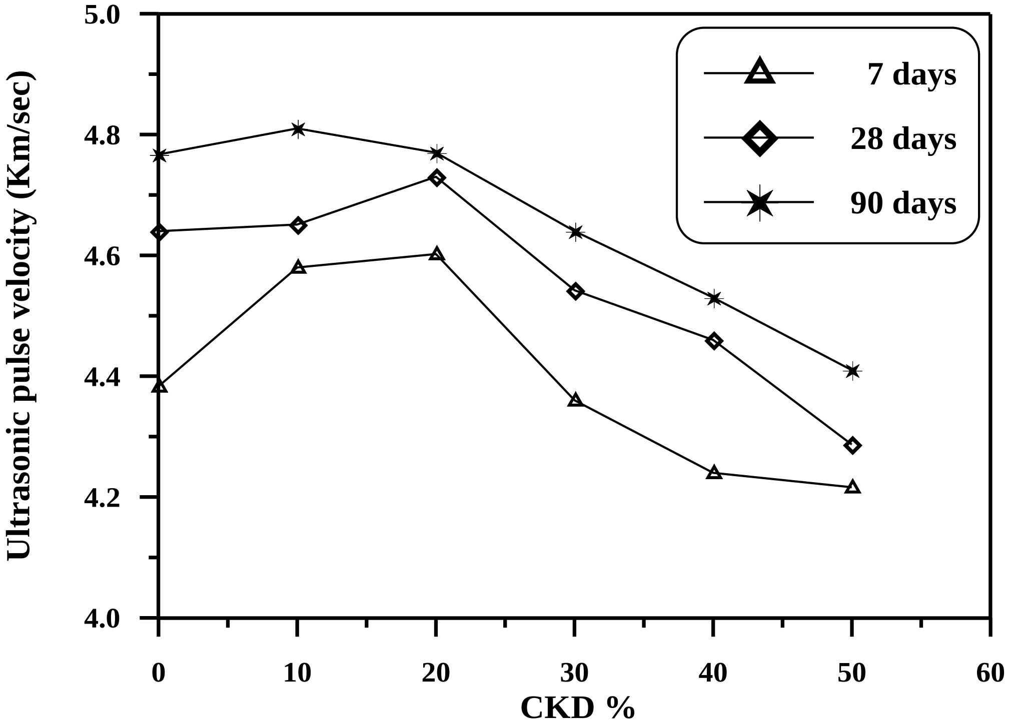

Fig.(٤-٣٥): Ultrasonic pulse velocity of concrete with additions of CKD as percentages of sand (series SRA).

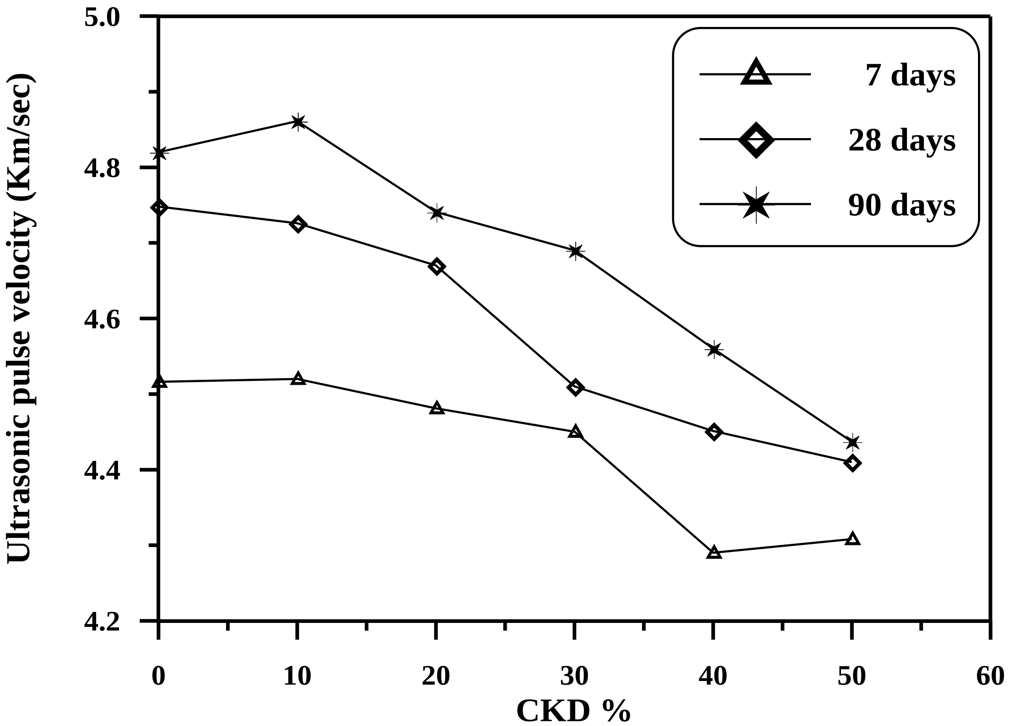

Fig.(٤-٣٦): Ultrasonic pulse velocity of concrete with additions of CKD as percentages of sand (series SRB).

Figs.(٤-٣٧) and (٤-٣٨) show the relationship between compressive strength of concrete and pulse velocity for ages from ٧ to ٩٠ days. In general, the increase in compressive strength leads to increase the pulse velocity. This is also true for concrete mixes containing CKD. However, an empirical formula can be suggested for this work:

For series CRA and CRB:

$$F_{cu} = 0.239\, e^{1.052V} \qquad \text{...........(٤-٣)}$$

For series SRA and SRB:

$$F_{cu} = 0.179\, e^{1.114V} \qquad \text{...........(٤-٤)}$$

where:

F_{cu} = compressive strength of ١٥٠ mm concrete cube, MPa.

V = ultrasonic pulse velocity of concrete, km/sec.

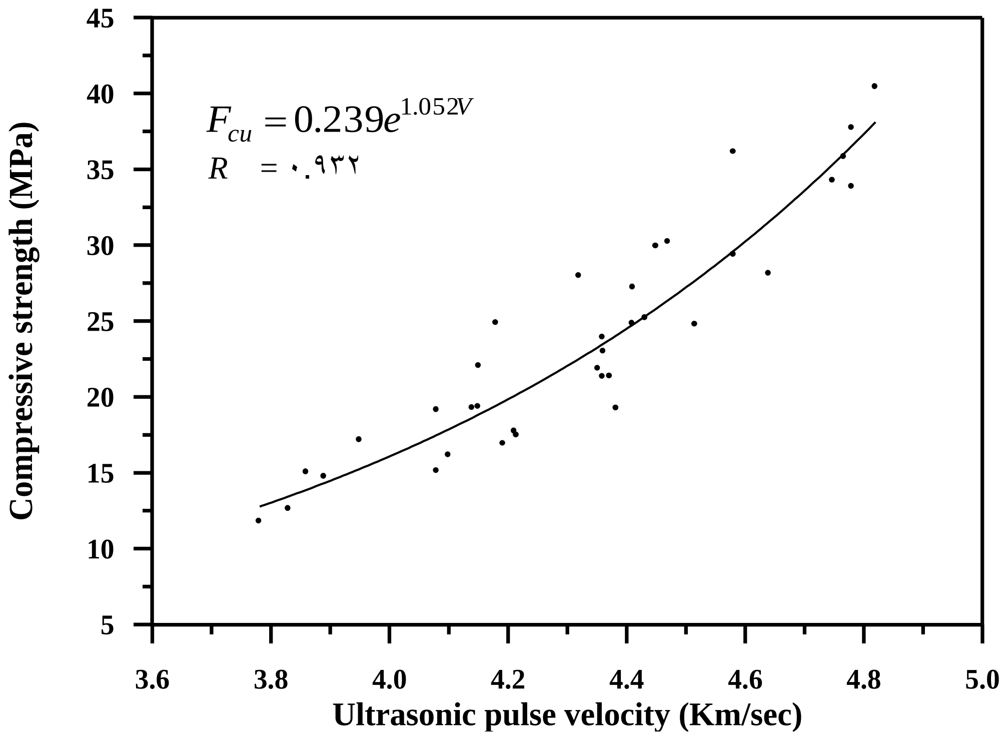

Fig.(٤-٣٧): Relationship between the ultrasonic pulse velocity and compressive strength of concrete for different ages and percentages of CKD as cement replacement (series CRA and CRB).

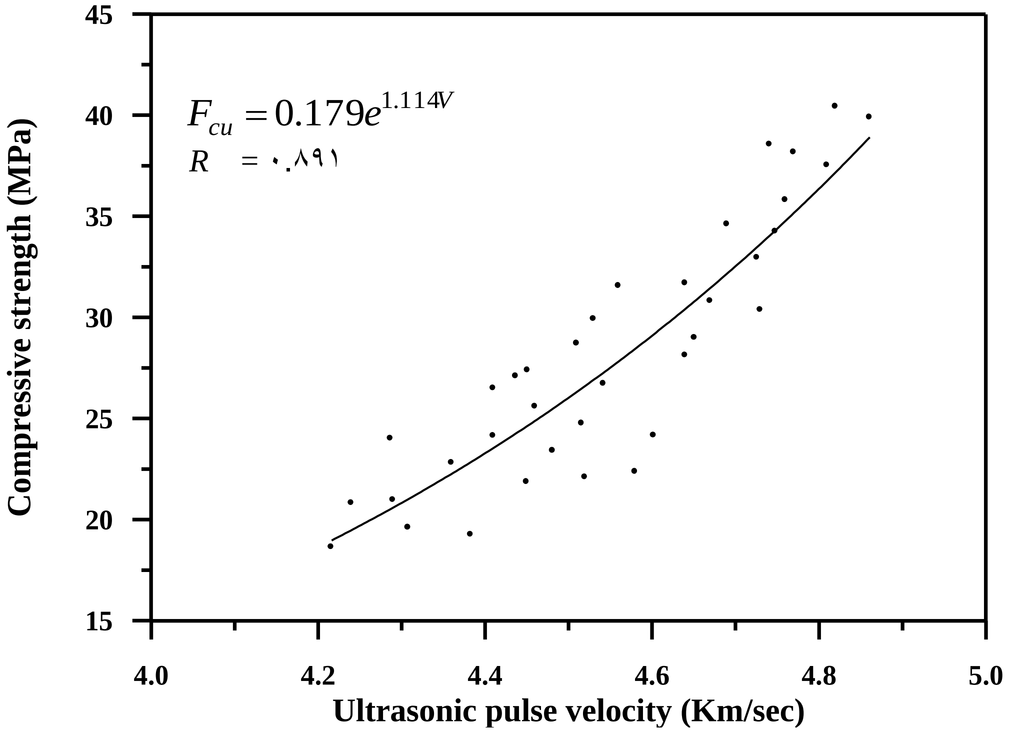

Fig.(٤-٣٨): Relationship between the ultrasonic pulse velocity and compressive strength of concrete for different ages and percentages of CKD as sand replacement (series SRA and SRB).

٤.٩ Drying Shrinkage Test Results

Drying shrinkage strains of mortar samples containing cement and sand replacement by CKD were measured for a period of ١٨٠ days after an initial curing of ٧ days in water.

The results of drying shrinkage tests for replacing cement and sand by CKD are presented in Table (٤-١٠) which shows that shrinkage strains increase with increasing the amount of replacement by CKD. In general, CKD shows no significant effect on the shrinkage strains when it is used as cement replacement, see Fig.(٤-٣٩). At high levels of replacement (mix CRL-٤٠), the shrinkage after ١٨٠ days is only ١٥٪ more than that of the control mix (CRL-٠). Fig.(٤-٣٩) also shows high shrinkage at early age of drying due to rapid loss of moisture from the surface of specimens. At later ages, the increase in the shrinkage is reduced with time depending on the moisture movement of specimens.

Table (٤-١٠): Effect of replacing cement and sand by CKD on drying shrinkage strain of mortar specimens.

Mix Series		Specimen mark	Drying shrinkage strain × ١٠⁻٦						
			١٤ days	٢٠ days	٢٨ days	٦٠ days	٩٠ days	١٢٠ days	١٨٠ days
Replacing cement by CKD	CRL	CRL-٠	٢٣٣	٣٧٨	٤٥٧	٥٩٧	٦٤٥	٦٩٥	٧٨٠
		CRL-١٠	١٥٧	٢٦٩	٤١٦	٦٣٦	٦٥٣	٧١٤	٨١٦
		CRL-٢٠	١٦٧	٣٠٢	٤٤٠	٦٥١	٦٩٥	٧٤٦	٨٨٨
		CRL-٣٠	١٩٣	٤٨٢	٥٥٧	٧٠٤	٧٣٣	٨٠٥	٨٩٨
		CRL-٤٠	٣٤٢	٥٥٧	٦٤٨	٧٦٠	٨٢٢	٨٦١	٩٢٢
Replacing sand by CKD	SRL	SRL-٠	٢٣٣	٣٧٨	٤٥٧	٥٩٧	٦٤٥	٦٩٥	٧٨٠
		SRL-١٠	٢٧٩	٤٤٧	٥٧٢	٧٦٧	٧٩١	٨٥٠	٨٥٩
		SRL-٢٠	٣٥١	٦١٨	٧٨٠	٩٢٠	٩٨٧	١١٠٦	١١٧٥
		SRL-٣٠	٣٩٨	٧٥٥	٩١١	١٠٩١	١١٦٣	١٢١٨	١٤٢٠
		SRL-٤٠	٣٦٧	٧٨٦	١٠٤٠	١١٩١	١٢٥٥	١٣٨٠	١٤٤٧

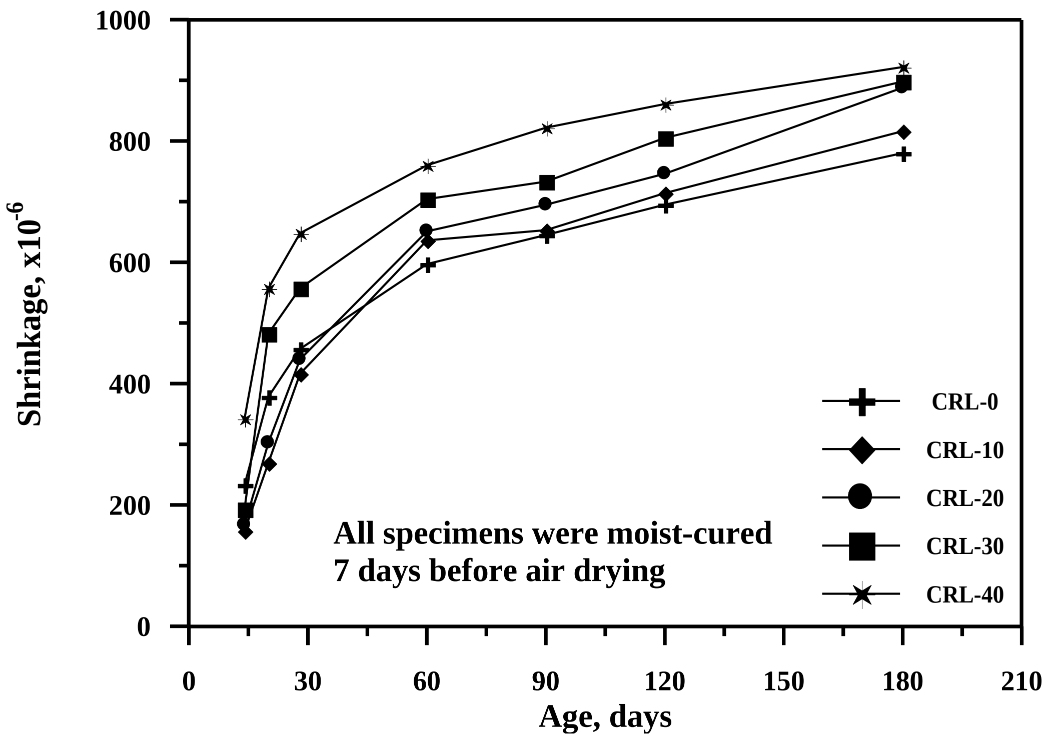

Fig.(٤-٣٩): Drying shrinkage strains versus age for mortar containing different percentages of CKD as cement replacement (series CRL).

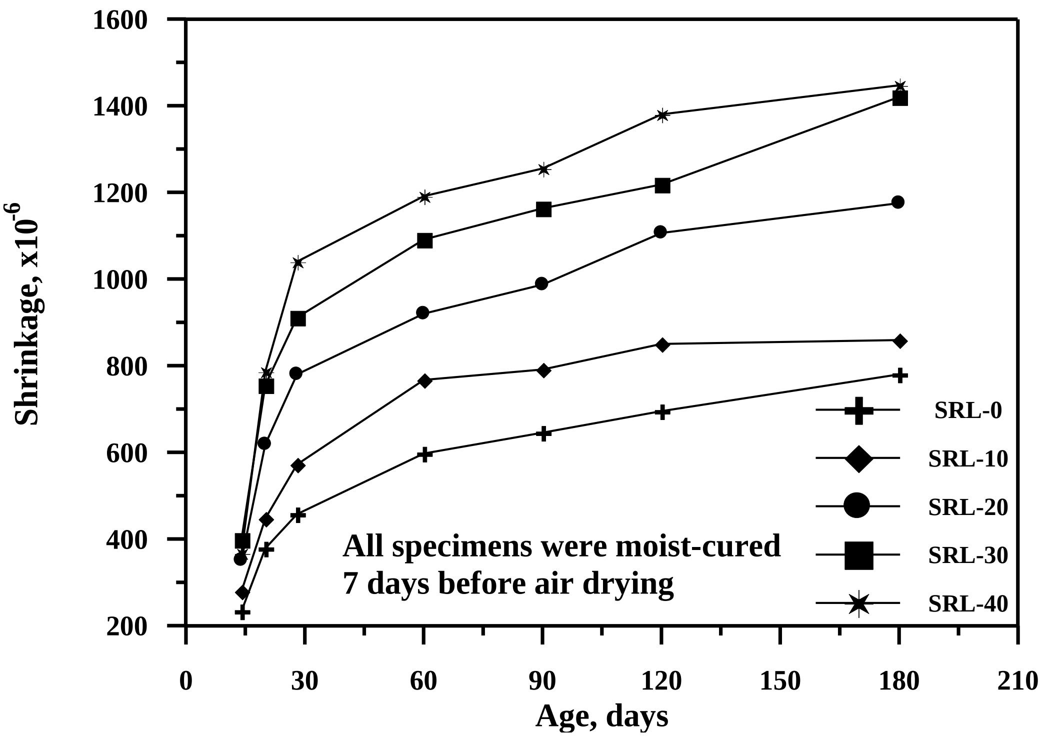

Fig.(٤-٤٠): Drying shrinkage strains versus age for mortar containing different percentages of CKD as sand replacement (series SRL).

The effect of CKD on shrinkage is more pronounced when it is used as sand replacement, see Fig.(٤-٤٠). This effect is particularly significant for mortars containing more than ١٠٪ of CKD. For example, after ١٨٠ days, the shrinkage of mortar specimens at the ١٠٪ CKD replacement of sand exceeds that of the control mix by about ١٠٪ as compared with about ٥١٪ at the ٢٠٪ replacement.

This increase can be attributed to the nature of the fine material which increases the shrinkage. Also, replacement of sand by CKD leads to decrease the sand content in the mix, which is mainly responsible for restraining shrinkage. On the other hand, the greater water demand for a given workability when CKD is used as sand replacement leads to greater shrinkage, especially at the higher contents of CKD.

٤.١٠ Expansion Test Results

Expansion strain data for both cement and sand replacement by CKD are summerized in Table (٤-١١). Expansion specimens were exposed to wet conditions for a period of ١٨٠ days.

It is found that the expansion of mortar specimens containing ١٠٪ of CKD in cement and sand replacement is slightly more than that of the control mixes. See Figs.(٤-٤١) and (٤-٤٢). However, the expansion increases significantly with the additions of higher percentages of CKD. For replacing cement by CKD, the increase in expansion after ٩٠ days ranges from about ٢٥٪ at the ١٠٪ CKD replacement level to about ٥٣٪ at the ٢٠٪ replacement level.

For replacing sand by CKD, the results also show that the expansion after ٩٠ days of specimens containing ١٠ and ٢٠ percent of CKD (mix SRL-١٠ and SRL-٢٠) are about ٣٦ and ٧٨ percent respectively more than that of the control mix (mix SRL-٠), and more than twice the value of the control mix for ٣٠٪ CKD replacement. Since CKD is rich in sulphate and alkali contents, it is possible that its presence in high levels may lead to the formation of large amounts of hydration products which lead to a considerable expansion of specimens. However, the effect of CKD as sand replacement on expansion is found to be somewhat similar to that on shrinkage.

Table (٤-١١): Expansion of mortar specimens when CKD is used as partial cement and sand replacement.

Mix Series		Specimen mark	Expansion strain $\times ١٠^{-٦}$								
			٣ days	٧ days	١٤ days	٢٠ days	٢٨ days	٦٠ days	٩٠ days	١٢٠ days	١٨٠ days
Replacing cement by CKD	CRL	CRL-٠	١٠٩	١٣٠	١٩٦	٢٠٥	٢١٤	٢٣١	٢٤٢	٢٣٤	٢١٩
		CRL-١٠	١٠٦	١١٥	١٦٥	١٩٠	١٩٥	٣٠٠	٣٠٧	٢٩٤	٢٨٨
		CRL-٢٠	١١٦	١٦٥	٢١١	٢٣٣	٢٤١	٣٢٨	٣٧٠	٤٠٣	٤١١
		CRL-٣٠	١٢٧	١٦٨	٢٥٠	٢٥٥	٢٩١	٤١٢	٤٨٠	٥٤١	٥٦٠
		CRL-٤٠	١٣٦	١٥٨	٢٦١	٣٣٩	٣٦٥	٤٢٧	٥٤٦	٦٣٩	٦٨٧
Replacing sand by CKD	SRL	SRL-٠	١٠٩	١٣٠	١٩٦	٢٠٥	٢١٤	٢٣١	٢٤٢	٢٣٤	٢١٩
		SRL-١٠	١٣٠	١٧١	٢٣٠	٢٥٣	٢٦٨	٣٣٠	٣٤٦	٣٧٧	٤١٠
		SRL-٢٠	١٤٢	١٩٠	٢٥٩	٢٧٤	٣١٥	٤٠٣	٤٣٣	٤٤٧	٤٥٨
		SRL-٣٠	١٦٩	٢٧٠	٣٣٩	٣٧٥	٤٤٦	٦٢٥	٦٦٨	٦٨٥	٧٤٣
		SRL-٤٠	١٧٨	٣٠٥	٣٧٩	٤٣١	٥٠٦	٦٦٠	٦٧٥	٧٠٣	٨١٤

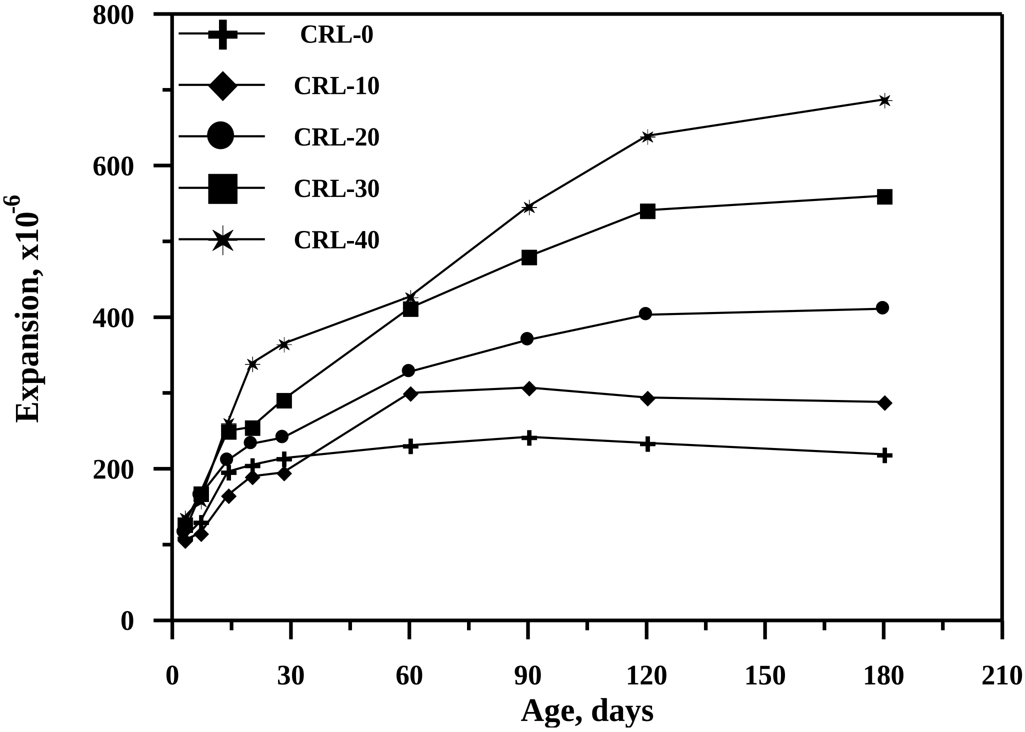

Fig.(٤-٤١): Expansion strains of mortar versus curing time when CKD is used as cement replacement (series CRL).

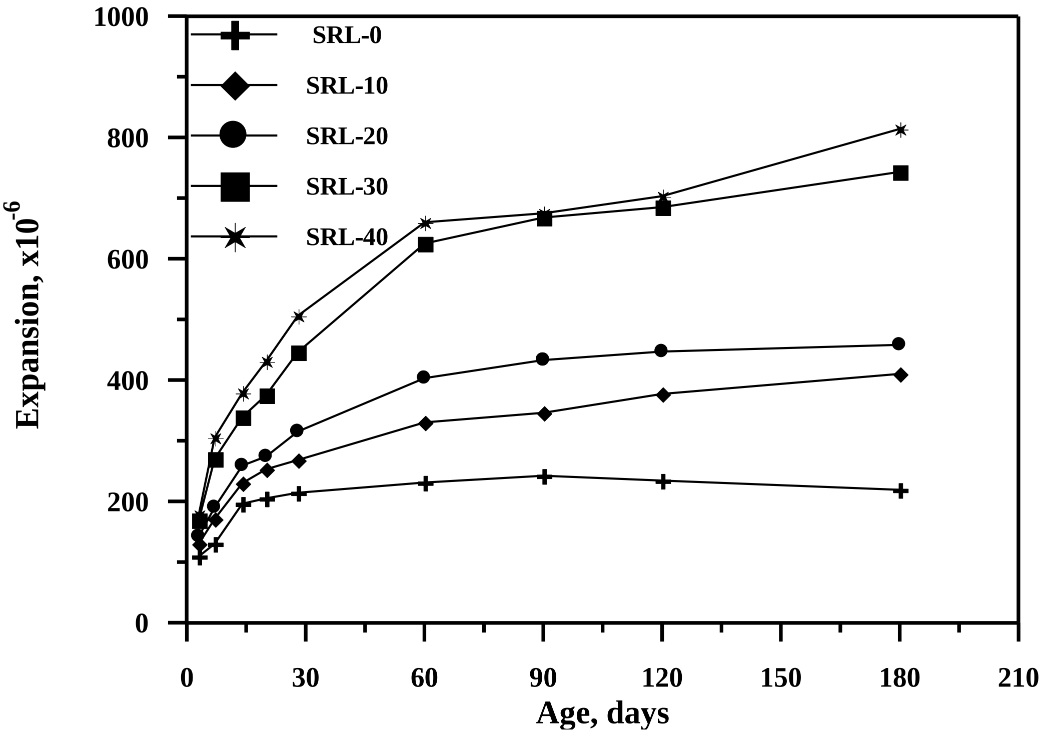

Fig.(٤-٤٢): Expansion strains of mortar versus curing time when CKD is used as sand replacement (series SRL).

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

٥.١ Conclusions

Based on the results of the experimental work of this study, the following conclusions can be drawn.

٥.١.١ Workability

١. The workability of concrete or mortar mixes is slightly affected when CKD is used as a partial cement substitution.

٢. For the partial substitution of sand by CKD, the water demand to produce the same workability increases with the increase in CKD content. Up to ٢٠٪ of CKD, the water demand is slightly higher than that of the control mix.

٥.١.٢ Compressive Strength

١. Replacement of cement by CKD has resulted in decreasing the compressive strength of concrete. Up to ١٠٪ of cement replacement, the magnitude of strength reduction at ٢٨ days is about ٨ and ١٠ percent for ١:٢:٤ and ١:١.٥:٣ mixes respectively.

٢. The presence of CKD as partial substitution of cement leads to reduce the compressive strength of mortar. At ٢٨ days, the strength of mortar specimens with up to ١٠٪ of cement replacement reachs about ٩٥٪ of the control mix strength for both ١:٣ and ١:٢ mixes.

٣. The presence of CKD as partial sand replacement in concrete increases the compressive strength of lean mixes. It was found that the best strength has been achieved in the mix of ١:٢:٤ with ٢٠٪ of CKD. At this level, the increase in compressive strength is about ٢٥.٥ and ٨ percent at the ages of ٧ and ٢٨ days respectively. While in the rich mix (١:١.٥:٣), the presence of CKD as a partial substitution of sand leads to reduce the compressive strength, and this reduction is about ٤٪ lower than that of the control mix when ١٠٪ of CKD is used. This means that the compressive strength of concrete containing CKD as a partial replacement of sand is significantly affected by the mix proportions.

٤. The effect of replacing sand by CKD on the compressive strength of concrete mixes appears more clearly at the age of ٧ days. It was found at this age that replacing ٢٠ and ٣٠ percent of sand by CKD in ١:٢:٤ mix develops ٨٠ to ٨٦ percent of the ٢٨ days strength, whereas it is about ٦٨.٥ percent for the control mix.

٥. The effect of CKD as a partial replacement of sand on the mortar has shown an increase in compressive strength up to ٢٠٪ in mix ١:٣, and up to ١٠٪ in mix ١:٢. At ٢٨ days, the best strength has been achieved at ١٠٪ of sand replacement by CKD. The compressive strength at this level is ١٣ and ٧ percent more than that of the control mix in ١:٣ and ١:٢ mix respectively.

٥.١.٣ Tensile Strength

١. The tensile strength of concrete measured by modulus of rupture and splitting tensile strength tests is lower than that of the control mix when CKD is used as a partial replacement of cement. The tensile strength reduction ranges from about ٥.٥ to ١٠ percent when ١٠٪ of CKD is used as partial cement replacement. But the addition of up to ٢٠٪ of CKD as sand replacement increases the tensile strength of relatively lean concrete (١:٢:٤ mix) by about ٨.٥٪ at the age of ٢٨ days.

٢. At high levels of both cement and sand replacement, the tensile strength of concrete containing CKD is more affected than compressive strength of the corresponding concrete, especially at the age of ٩٠ days.

٥.١.٤ Density and Ultrasonic Pulse Velocity

١. The density of concrete specimens in both cement and sand replacement by CKD are generally found to decrease with the increase in the percentages of CKD. It was found that the density of specimens in cement and sand replacement ranges between (٢٢٨٦ to ٢٤٠٣) and (٢٣١٢ to ٢٤٠٣) kg/m٣ respectively.

٢. The ultrasonic pulse velocity is affected by replacing cement by CKD. Generally, as the percentage of CKD increases, the concrete show decreasing in pulse velocity, reflecting the decrease in compressive strength, tensile strength as well as the density of the specimens. When CKD is used as partial sand replacement, it was found that the presence of up to ٢٠٪ of CKD in ١:٢:٤ mix has shown an increase in the pulse velocity of the concrete samples.

٥.١.٥ Drying Shrinkage and Expansion

١. The presence of CKD shows no significant effect on shrinkage strains when it is used as cement replacement. At high levels of cement replacement (٤٠٪ of CKD by weight of cement), the shrinkage after ١٨٠ days is only ١٥٪ more than that of the control mix. But the effect of CKD on shrinkage is more pronounced when it is used as sand replacement. This effect is particularly significant for mortars containing more than ١٠٪ of CKD by weight of sand.

٢. The expansion of mortar specimens containing ١٠٪ of CKD as cement or sand replacement is slightly more than that of the control mix. But the expansion increases significantly with the presence of higher percentages of CKD.

٥.١.٦ Optimum Percentages of CKD

١. From the study reported here, it can be stated that ordinary Portland cement could be replaced by up to ١٠٪ of CKD in concrete and mortar mixes. At this level of replacement, CKD could be suitable for usage in concrete or mortar production and this can result in savings in construction costs.

٢. It was found also that the upper limit of replacing sand by CKD in lean mixes is not more than ٢٠ percent in both concrete and mortar mixes. At this level, the concrete and mortar have a strength more than that of the control mixes. For the mixes which are rich in cement, the study has shown that there is little effect when using CKD as sand replacement.

٥.٢ Recommendations for Future Work

As there are limited data avilable for usage CKD in concrete, further investigations in the following fields are suggested.

١. Further studies are needed to evaluate some potential applications for the utilization of CKD in the cement industry, such as the ability of recycling CKD with cement raw materials.

٢. The effect of CKD on the properties of concrete and mortar mixes using different curing conditions should be investigated.

٣. Further research is required to investigate some other properties of concrete containing CKD, such as creep, modulus of elasticity, absorption and thermal conductivity.

٤. Further experimental work on long term durability is necessary to evaluate the performance of concrete and mortar incorporating CKD. The durability problems when using CKD may come from the fact that adverse reactions could result if alkalies, sulphates and chlorides contents in the mix are considerable.

٥. Data are needed to investigate the same problem using superplasticizers,especially when CKD is used as sand replacement.

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APPENDIX A

Table (A-١): Physical properties of the cement

Physical Properties	Test results	IOS ٥: ١٩٨٤[٦١] Limits
Fineness, Blaine, cm^{٢}/gm	٣٠٦٠	≥ ٢٣٠٠
Setting time, Vicat's method		
Initial hrs: min.	١:٥٤	≥ ١: ٠٠
Final hrs: min.	٣:٣٥	≤ ١٠: ٠٠
Compressive strength of ٧٠.٧ mm cube, MPa		
٣ days	٢٢	≥ ١٥
٧ days	٢٨	≥ ٢٣

Table (A-٢): Chemical composition of the cement

Oxide	(%)	IOS ٥: ١٩٨٤[٦١] Limits
CaO	٦١.٢٦	
$SiO_{٢}$	٢٠.٨٠	
$Fe_{٢}O_{٣}$	٣.٢٠	
$Al_{٢}O_{٣}$	٦.١٢	
MgO	٤.٤٠	≤ ٥.٠
$SO_{٣}$	٢.٣٣	≤ ٢.٨
Free lime	٠.٧٦	
L.O.I.	١.٧٥	≤ ٤.٠
I.R.	٠.٦١	≤ ١.٥
Compound composition	**(%)**	**IOS ٥: ١٩٨٤[٦١] Limits**
$C_{٣}S$	٣٥.٨٨	
$C_{٢}S$	٣٢.٥٦	
$C_{٣}A$	١٠.٨٠	
$C_{٤}AF$	٩.٧٣	
L.S.F.	٠.٨٨	٠.٦٦-١.٠٢

Table (A-٣): Properties of the sand

Sieve size (mm)	**Percent passing**	**IOS ٤٥: ١٩٨٤[٦٢] Limits, Zone ٣**
٩.٥	١٠٠	١٠٠
٤.٧٥	٩٥	٩٠-١٠٠
٢.٣٦	٩٣	٨٥-١٠٠
١.١٨	٧٩	٧٥-١٠٠
٠.٦	٦١	٦٠-٧٩
٠.٣	٢٨	١٢-٤٠
٠.١٥	٠	٠-١٠
Properties	**Test results**	**IOS ٤٥ : ١٩٨٤[٦٢] Limits**
Sulphate content, $SO_{٣}$ (%)	٠.٢٧	≤ ٠.٥
Specific gravity	٢.٦٠	
Absorption (%)	١.٦	

Table (A-٤): Properties of the gravel

Sieve size (mm)	Percent passing	IOS ٤٥ : ١٩٨٤ (٦٢) Limits
٣٧.٥	١٠٠	١٠٠
٢٠	١٠٠	٩٥-١٠٠
٩.٥	٥١	٣٠-٦٠
٤.٧٥	٤	٠-١٠
Properties	**Test results**	**IOS ٤٥: ١٩٨٤ (٦٢) Limits**
Sulphate content, SO٣ (%)	٠.٠٨	≤ ٠.١
Specific gravity	٢.٦٤	
Absorption (%)	٠.٨	